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About Authors

• **John Ryle MacGregor** *flew into the oil business via the 316th Squadron, U. S. Army Air Service of which he served as engineering officer after graduating from the U. S. Flying School at Brooks Field, Texas. He has been everything from laboratory assistant to specialist in charge of fuel and lubricants testing in the S. O. of Calif. organization where he has worked continuously since 1925. Since 1933 he has concentrated on fuel research and is an active member of practically all those committees with long names which have been studying automobile, aviation and Diesel fuels under C.F.R. and SAE auspices. He began his professional career with a B.S. in M.E. from University of California in 1924.*

• **T. B. Rendel** *came to United States as test engineer for Shell in 1927, promptly joined the SAE and has been active in the Society's fuel research ever since. Now he is in charge of Shell's automotive research laboratory here and is SAE vice-president representing fuels and lubricants. He has just returned from a visit to his native England and to his company's main headquarters in Holland. His engineering degree came from Clare College, Cambridge University, although he also attended Royal Naval College at Dartmouth.*

• **Robert B. Schenck** *went to work for Buick when there were only 7½ million automobiles running in the United States and alloy steels were in their swaddling clothes. He has had an active role ever since in the remarkable metallurgical developments of the past 17 years. Although born in Beacon, N. Y., he has been in sight of a steel mill ever since he went to Lehigh, from which he was graduated in 1909. He worked with Carnegie Steel at Homestead before moving into his first automotive connection with Western Mott Co.*

• **Raymond W. Young** *was born in Missouri and has been making facts prove themselves to him ever since. Experimenting, researching, testing has been his forte ever since he undertook post-graduate work in automotive engineering research at Yale after getting his M.E. degree there in 1922. He went to Wright Aeronautical Corp. from Yale in 1925 and has been there ever since in capacity of test engineer, experimental engineer, executive engineer and assistant engineer.*

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Diesel Fuels — Significance of Ignition Characteristics

By J. R. MacGregor
Standard Oil Co. of Calif.

DATA are presented showing the results of extensive tests of Diesel fuels of widely different ignition characteristics in laboratory and service engines. The tests in laboratory engines are particularly significant in demonstrating the influence of controlled differences in operating conditions upon the relative ease of ignition of fuels.

The tests in service engines show that each engine has distinct minimum requirements for fuel-ignition quality; that the minimum required is different under different operating conditions; and that no essential difference in the performance of fuels can be noted as long as the minimum ignition quality is exceeded. For all practical purposes, therefore, no correlation appears possible between the laboratory rating of Diesel fuel ignition characteristics and service behavior.

The conclusion is advanced that, since fuels equal or superior to the minimum for any engine are required to secure freedom from the difficulties attending incomplete combustion and since no essential differences can be noted between fuels exceeding the minimum quality, the development of laboratory tests for evaluating the ignition characteristics of fuels is of primary utility at the present time in aiding the engine manufacturer to secure experimental fuels of known ignition quality to further the development of engine design.

THE advent of the high-speed automotive-type Diesel engine has introduced combustion-control problems that were previously of no importance in the large slow-speed engines of marine and stationary installations. In order to compete on a weight and volume basis with the well-established gasoline engine, it was necessary to use relatively small cylinders in the newer Diesel engines and to operate them at speeds previously considered impossible.

However, these new automotive-type engines frequently encountered combustion difficulties, and the early works of Pope and Murdock[1] and Boerlage and Broeze[2] indicated that under certain operating conditions the characteristics of the fuel used caused differences in engine operation. The works of these investigators are well known and resulted in two proposed methods of rating the ignition quality of Diesel fuels. Pope and Murdock suggested the determination of the "critical compression ratio" of the fuel in a modified C.F.R. knock-testing engine under specified conditions. Boerlage and Broeze, on the other hand, recognizing the influence of mechanical and barometric changes on the performance of their test engine, suggested the bracketing of unknown fuels between blends of the pure compounds, cetene and mesitylene.

It was realized that, if ignition-quality tests were to be made on Diesel fuels, a standardized procedure was required to enable one laboratory to talk in terms of another laboratory's results. The Volunteer Group for Research on Compression-Ignition Fuels was formed and has undertaken the establishment of a reproducible test method for this purpose. The activities of this Group have been reported from time to time, and the results are well known to those interested in the problem.

During this period engine builders recognized the influence that design might have on the ability of an engine to utilize fuels shown to have poor ignition quality by any of the then-established test methods and experimented with combustion-chamber design. Fig. 1 shows the distribution of combustion-chamber types for the years prior to 1935 during which records were available, for American, British, and German manufacture. In preparing this chart the percentages have been calculated on the basis of the total number of models offered and do not consider the number of those models actually used in service. Number of models, however, affords an index of the designer's thoughts and of the means employed by him in attempting to secure the desired results. It will be noted

[This paper was presented at the Annual Meeting of the Society, Detroit, Mich., Jan. 14, 1936.]

[1] See S.A.E. TRANSACTIONS, March, 1932, pp. 136-142; "Compression-Ignition Characteristics of Injection-Engine Fuels", by A. W. Pope, Jr., and J. A. Murdock.

[2] See S.A.E. TRANSACTIONS, July, 1932, pp. 283-293; "Ignition Quality of Diesel Fuels as Expressed in Cetene Numbers", by G. D. Boerlage and J. J. Broeze.

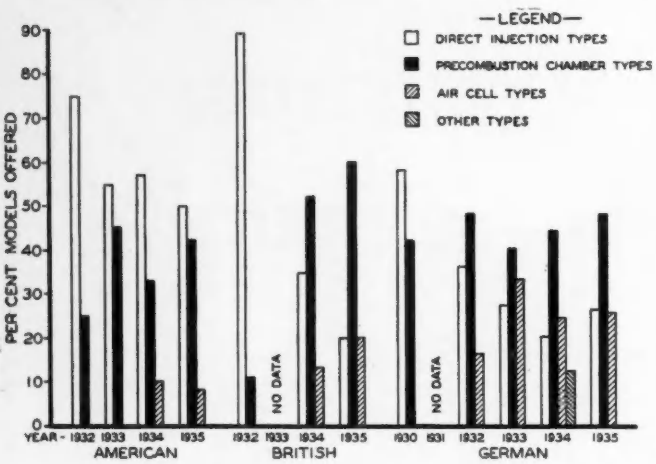


Fig. 1—Automotive Diesel Engine Trends—Combustion-Chamber Design

that well-established trends are not apparent although, broadly speaking, the direct-injection engine has lost in popularity over this period of time. A possible exception may be noted in the case of Germany where a slight return to the use of this principle may be observed in 1935.

Automotive Diesel engines are adaptable primarily to the powering of large commercial vehicles of the truck and bus type. Operators of fleets of this class depend entirely upon the revenue obtained from their units for their profits and, in most cases, employ careful cost-accounting systems to establish the actual value of any equipment used. As an illustration, C. T. Anthony presented a paper at the American Petroleum Institute meeting in Los Angeles in November, which showed how closely the Pacific Freight Lines watch costs of this nature. It is apparent therefore that, if Diesel engines are to require a variety of different fuels, the engine capable of satisfactorily using the least expensive fuel will show up to considerable advantage when subjected to the scrutiny of a cost analyst. A Diesel engine's ability to use satisfactorily a wide range of fuels is of particular importance since, unlike the gasoline engine that can operate more efficiently when utilizing the higher compression ratios made possible by high-octane gasolines, increased power and economy do not necessarily accompany an increase in the ignition quality of the fuel used. In this paper consideration is confined to the importance of ignition quality only and assumes equally clean fuel in all cases.

The method originally developed and still used in our laboratory for the routine rating of Diesel fuels is a modification of that proposed by Pope and Murdock. This method has been described previously to the Society[8] and is identified as the Standard Oil Co. of Calif. 600 R.P.M. Starting Method in order to eliminate the possibility of confusing the results with those obtained by the Pope and Murdock method since they are not directly comparable. Briefly, our method utilizes the converted C.F.R. knock-testing engine equipped with the automatic injection timer for admitting fuel for 2 successive injections followed by 28 injection periods during which no fuel is permitted to enter the cylinder. Removal of all unburned fuel and products of combustion is thus accomplished, which removal permits the injected fuel to enter entirely clean air. Although originally a lower injection pressure was used, this pressure has since been standardized at 2000 lb. per sq. in.

As will be shown later, the ignition-quality determination depends to some extent upon the injection pressure used, but 2000 lb. per sq. in. has been adopted as a compromise between operating difficulties and optimum requirements of the fuels tested. This pressure also is sufficiently high so that changes in compression pressure accompanying changes in compression ratio do not materially affect the spray characteristics. The occurrence of ignition is indicated by the flash of a neon tube actuated through an amplifying device by a spark-plug placed in the opening provided for the bouncing pin. Ionization of the material surrounding the spark-plug points occurs at the instant of flame passage, and the current thus passed causes the flash. The ignition quality of a fuel is determined by varying the compression ratio by increments until the point is reached where ignition just occurs, the compression pressure is determined and, from a frequently checked calibration curve, the cetane number is assigned.

In our method critical compression pressure (C.C.P.) has been used as the criterion, instead of critical compression ratio (C.C.R.), since the latter method is subject to mechanical and atmospheric variations. Our method has been found very reproducible, providing that the calibration between critical compression pressure and reference-fuel blends is frequently checked. Considerable confusion originally existed when results were reported in terms of cetene number because of the variations in that product, but this objection has been largely overcome by the use of cetane now being supplied by the Du Pont Co.

The essential problem in rating any product in the laboratory is the determination of the value of that laboratory method in predicting the service performance of the product in question. Realizing the differences existing in engine designs and the conditions under which those units are used, it was apparent that, if a single laboratory test could be considered indicative of service performance, minor changes in the method of carrying out that laboratory test should not alter the relative values of fuels.

In Fig. 2 a calibration of critical compression pressures in terms of cetane numbers is shown as obtained by our 600 r.p.m., starting-test procedure. In order to accentuate the relation shown by the calibration curve a second line has been

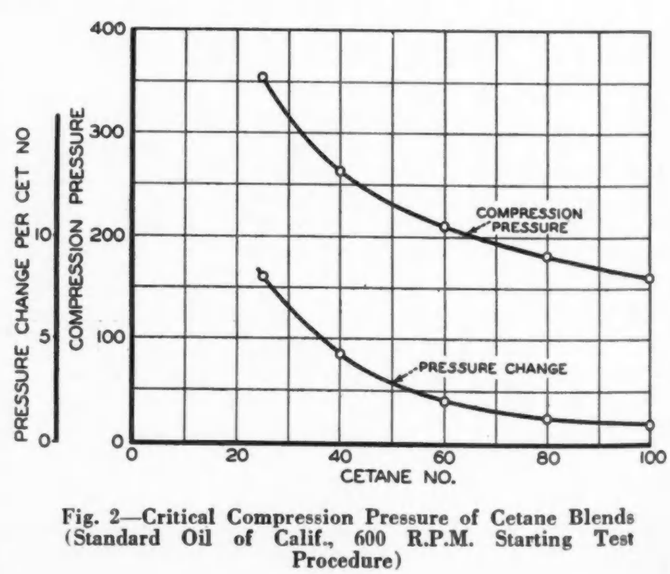


Fig. 2—Critical Compression Pressure of Cetane Blends (Standard Oil of Calif., 600 R.P.M. Starting Test Procedure)

[8] See S.A.E. TRANSACTIONS, October, 1934, pp. 380-381; discussion by J. R. MacGregor of "A Suggested Index of Diesel Performance", by A. E. Becker and H. G. M. Fischer.

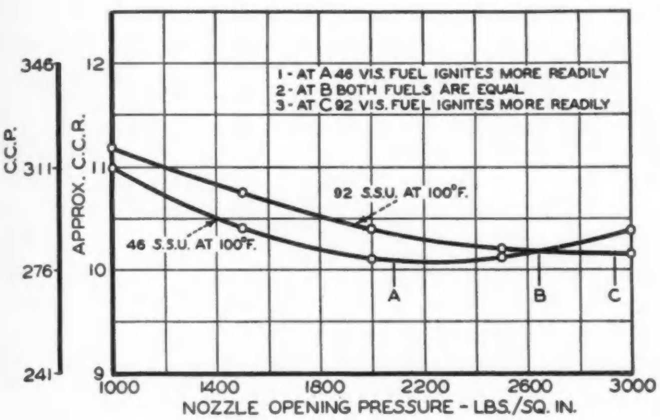


Fig. 3—Influence of Injection Pressure and Fuel Viscosity on Ease of Ignition (Standard Oil of Calif., 600 R.P.M. Starting Test Procedure)

included indicating the change in critical compression pressure per cetane number. It will be noted that in the lower range of cetane numbers the compression pressure can decrease by approximately 7½ lb. per sq. in. before a fuel having one cetane number higher ignition quality would be required. In

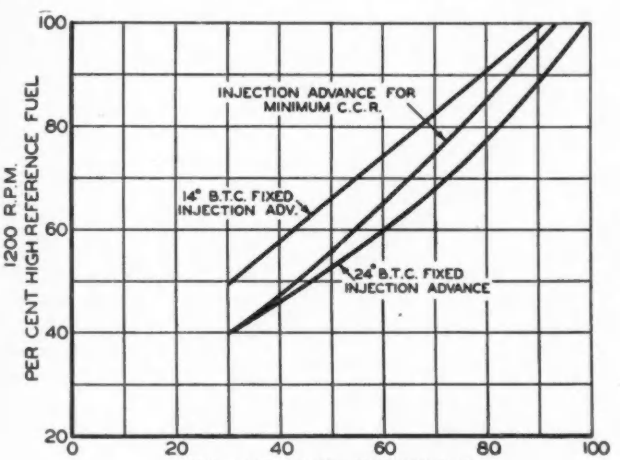


Fig. 4—Comparative Values of Fuel Quality Requiring Identical Compression Ratio for Ignition at 600 R.P.M. and 1200 R.P.M. (Standard Oil of Calif. Starting Test Procedure)

the higher range, however, a decrease in compression pressure of only about 1 lb. per sq. in. would require an increase of one cetane number in the fuel used. The shape of the curves demonstrated rather conclusively that the margin of safety in an engine requiring high cetane number fuel would, therefore, be considerably less than in an engine less sensitive to fuel requirements.

Fig. 3 shows the influence of injection pressure and fuel viscosity on ignition as determined by the same test procedure. For purpose of illustration, two fuels, one having a Saybolt viscosity of 46 sec. at 100 deg. fahr. and the other having a viscosity of 92 sec. Saybolt at 100 deg. fahr. were tested with nozzle-opening pressures varied between 1000 and 3000 lb. per sq. in. The approximate critical compression ratios have been plotted as ordinates since this criterion has been more widely used than the more exact critical compression pressure equivalents shown. It will be noted that, if the fuels are tested at the optimum injection pressure for the 46-sec. fuel as shown at *A*, the low-viscosity fuel will be found better than the high; at *B* both fuels are equal, while at *C* the high-viscosity fuel ignites more readily. This difference is not great but nevertheless amounts to several cetane numbers.

The speed of the engine was next increased to 1200 r.p.m. in order to determine the influence of this variable, and a group of blends of secondary reference fuels were tested under a variety of conditions but by a method similar to that used in our 600 r.p.m. tests. Fig. 4 shows that different blends of reference fuels were required to just obtain ignition at the same compression ratio at the two speeds shown. For example, at a fixed injection advance of 14 deg. before top-center, a blend containing 30 per cent high reference fuel would just ignite at a certain compression ratio, whereas at 1200 r.p.m. it would not. Ignition could not be obtained at the high speed and given compression ratio until the concentration of high reference fuel was increased to 50 per cent. By the same method it was found that a 91 per cent high reference fuel blend would ignite at the same compression ratio at 600 r.p.m. as the straight high reference standard when tested at 1200 r.p.m. Similar data are shown for an injection advance of 24 deg. before top-center and for injection advances adjusted in each case to give the minimum critical compression ratio. Again a variation in apparent fuel-ignition quality amounting to several cetane numbers is accounted for by minor changes in test conditions.

The tests so far discussed have considered the ease with which a fuel ignites under conditions not normally met in operating engines except possibly at the instant of starting when compression pressures and temperatures may be low. A method was therefore developed in which the ignition lag of the fuel was determined at 1200 r.p.m. with the engine running normally at a given fuel rate, and with the injection advance readjusted in each case for minimum lag. Fig. 5 shows the results obtained on two fuels at different compression ratios of test. It will be noted that at the compression ratios approaching those below which the fuels did not ignite, a considerable difference in ignition lag was found; whereas at high ratios very little difference was noted. This condition indicated that, in commercial engines where compression ratios of 14:1 or more are used, the fuels chosen as examples because of their 40 and 60 cetane number ratings by our 600 r.p.m.

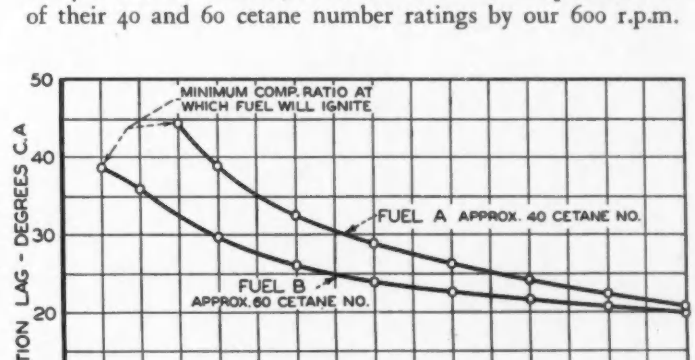


Fig. 5—Effect of Compression Ratio on Ignition Lag

Converted C.F.R. engine, 1200 r.p.m.; injection advance for minimum ignition lag; cetane number by Standard Oil of Calif., 600 r.p.m. starting test.

starting method might operate very nearly alike if the ignition lag of a fuel is of prime importance.

Mention has not been made of tests carried out in conjunction with the Volunteer Group as the results of that endeavor will be released from time to time. Suffice it to say that the relative ratings of fuels are frequently different when tested by this present tentative method and by the other methods discussed herein.

The laboratory tests from which the previously discussed data have been chosen for illustration demonstrated conclusively that the ignition quality of a fuel is not a single factor and must be considered in terms of the engine in which that fuel is to be used. It therefore seemed essential that, before continuing with the establishment of a highly reproducible laboratory test, service performance of a number of fuels shown to differ broadly by any of the laboratory tests should be determined under actual service conditions. Consequently a number of popular high-speed Diesel engines were obtained and set up in the laboratory to carry out these tests using fuels specially chosen or prepared to have a wide range of cetane numbers by our 600 r.p.m. starting test method.

Fig. 6 illustrates the type of set-up used with the multicylinder engines. Conventional means were provided for controlling power, speed, and temperatures; and special means were provided for measuring fuel consumption, exhaust-smoke density, and so on. The timing mechanism used for determining the time interval per unit of fuel consumed, starting tests, and so on is shown on the shelf at the dynamometer. This unit includes a double-trip-operated stop watch under electrical control of the unit being timed. Provisions are made for actuating additional circuits simultaneously with the starting and stopping of the watch. One use for these additional circuit controls is the actuation of the dynamometer counter as a check on speed.

The smoke meters used in all tests may be of interest since they have been built rather simply and have yielded very reproducible results. One of the units is shown in Fig. 7 and consists of a light source and a Photronic cell suitably mounted in pipe fittings. Both the cell and the light source are protected from fouling by glass screens, and each of the assemblies can be removed readily for cleaning. Valve means are provided for bypassing the exhaust through the unit only during the period when observations are to be made. A mild draft of air is provided on the exhaust side of both the light

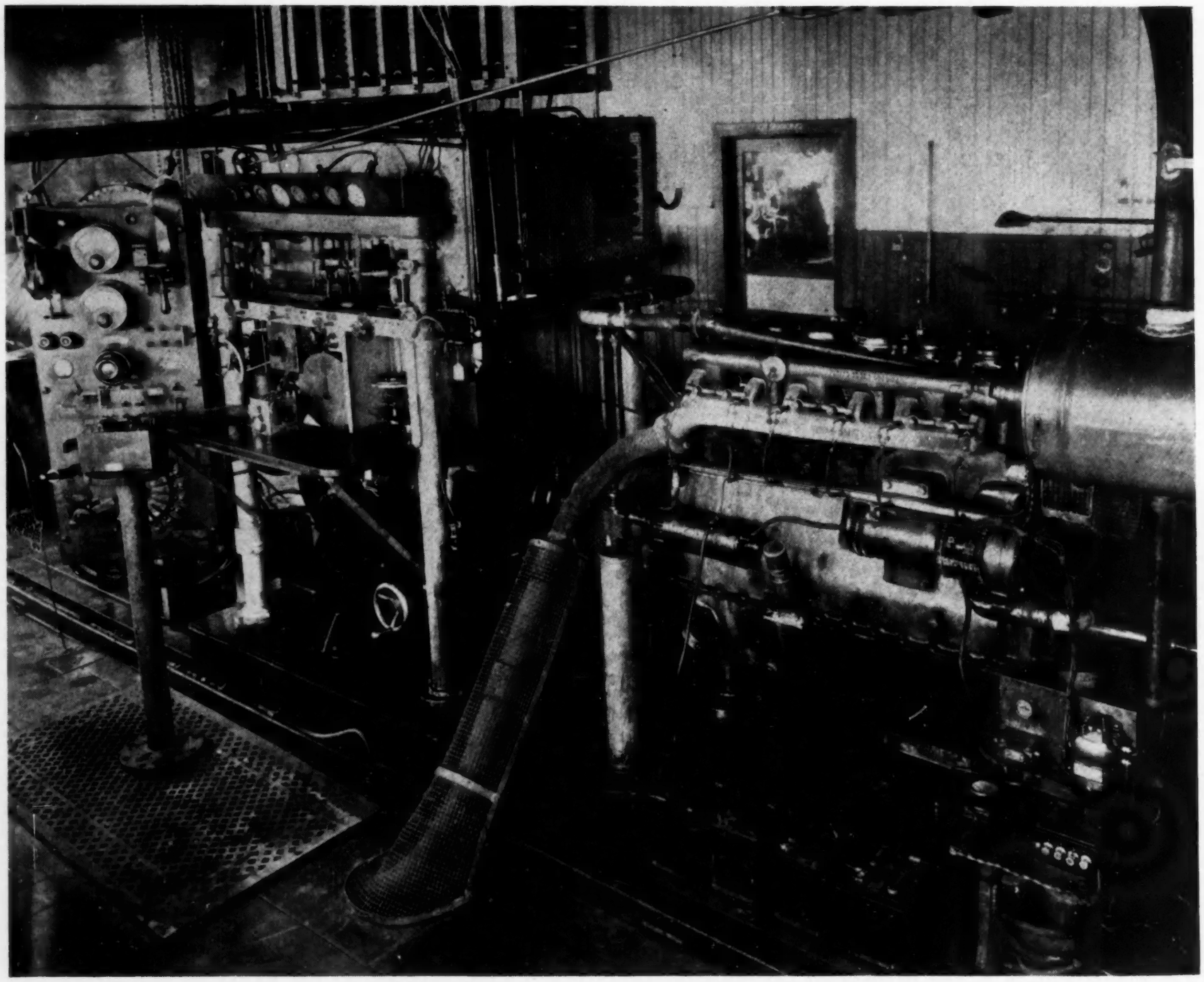
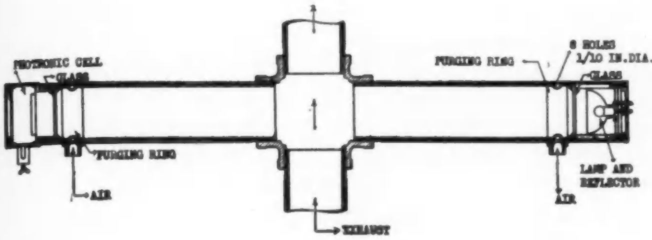


Fig. 6—Type of Set-Up Used with Multicylinder Engines



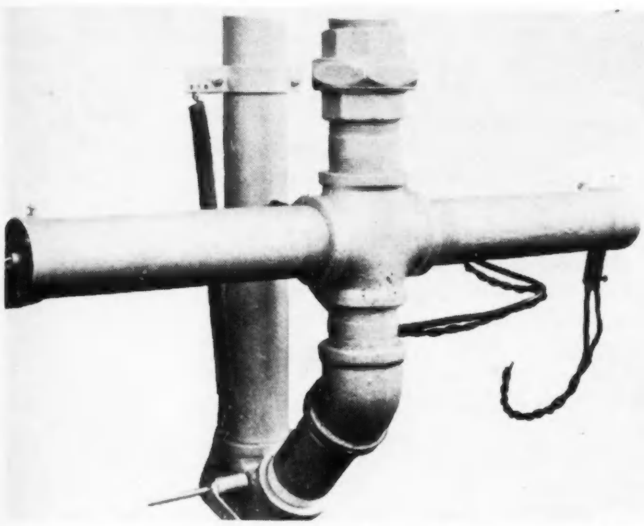


Fig. 7—Smoke Meter Showing Photronic Cell and Light Source

source and Photronic cell in order to purge the cross-arms of exhaust smoke at all times. In making a determination the minimum meter reading is first obtained with the lamp turned off to establish the "100 per cent smoke" point. The lamp is then turned on, and successive readings obtained in rapid succession with and without exhaust gas passing through the unit to determine the readings for the smoke and "0 smoke" conditions. Relative exhaust-smoke density is then assigned proportional to the 0 and 100 per cent smoke readings by reference to the calibration of the Photronic cell.

In evaluating the service performance of Diesel fuels consideration has been given to their ability to start at moderate and low temperatures and to the economy, power, knock, and exhaust smoke obtained under conditions of varying load speed, altitude, and so on.

All of the results obtained in tests of the nature considered cannot be covered in a brief paper, but certain of the relations found are presented to indicate the sensitivity of certain engines to fuel-ignition characteristics and the possibility of obtaining a laboratory test by which service performance can be predicted.

Starting tests, made on engine No. R.D. 1008, showed that at moderate temperatures, 60 to 70 deg. fahr., the engine would start immediately on any fuel tested. These fuels varied in cetane number, determined by our 600 r.p.m. starting method, from approximately 25 to 60, and started in all cases within 0.4 sec. At a temperature of 35 deg. fahr. the same ease of starting was obtained with all fuels having cetane numbers above approximately 35. Subsequent running on fuels of minimum cetane number was accompanied by blue-white smoke in the exhaust until the engine had become thoroughly warmed up. These starting times were determined by noting the interval between the time fuel was started to the engine and the time when the Bendix gear of the starter was thrown out of mesh with the flywheel gear. For this purpose special electric contacts were provided which actuated the timing mechanism previously mentioned. As no cold-room facilities were available for the low-temperature starting tests, refrigerating means were applied to the engine jacket and the air intake to the manifold.

Some engines are particularly critical to cranking speeds and will fail to start entirely unless this speed is above a certain minimum. The engines most critical in this respect are those using injection nozzles not equipped with loading springs. It is obvious that, unless such a spring is provided to insure a reasonable pressure before opening, extremely poor atomization will result when the pump speed is low.

Performance data obtained on the same engine at two operating speeds and using the 40- and 60-cetane fuels previously mentioned are shown in Fig. 8 for purposes of illustrating the performance under normal operating conditions. It will be noted that at 900 r.p.m. the density of the exhaust smoke is essentially identical for both fuels over the entire range of brake mean effective pressures. The fuel consumption with the 40-cetane fuel was equal or superior to that obtained with the 60-cetane fuel at all loads. At 1800 r.p.m., however, the 60-cetane fuel was slightly superior to the 40-cetane fuel in both fuel consumption and exhaust smoke. However, it is interesting to note that, due to the differences in weight per gallon of the two fuels, the one of low cetane rating is of material superiority if consumption were to be based on gallons consumed rather than pounds as shown.

Having found that the 40- and 60-cetane fuels, which cover approximately the range of commercially available products, operated in this engine with the same degree of satisfaction as regards ease of starting, power, economy, exhaust smoke, and knock, tests were then made to determine the lowest cetane number fuel that would give such satisfactory performance. In Fig. 9 the results obtained at approximately half load, or at a b.m.e.p. of 40 lb. per sq. in., are shown. It will be noted that at 900 r.p.m. the fuel consumption on all fuels having cetane numbers above 26 was the same; whereas poorer consumption and misfiring were obtained with fuels

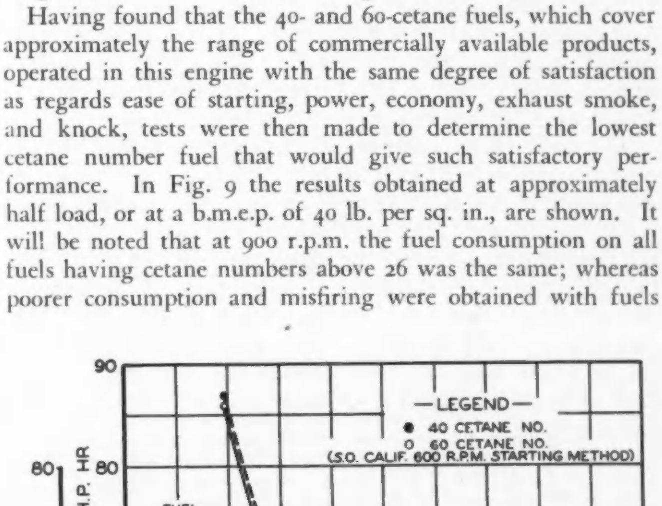


Fig. 8—Performance of Engine R.D.-1008

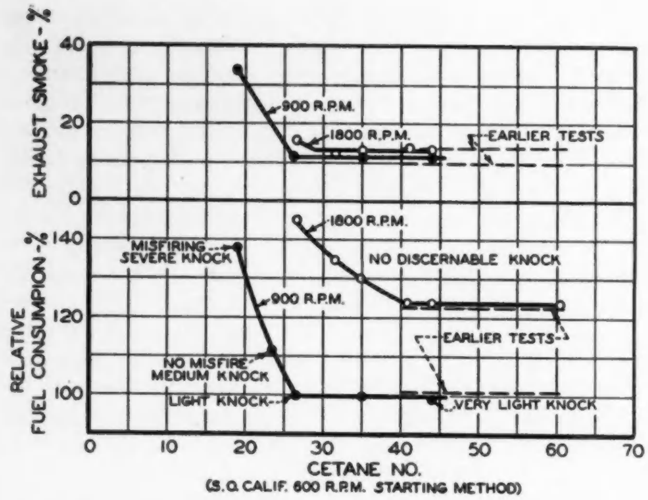


Fig. 9—Ignition Quality Requirements of Engine R.D.-1008
B.m.e.p. 40 lb. per sq. in.

of lower cetane number. At 1800 r.p.m. a similar condition was found to exist except that the critical cetane number was approximately 40. At intermediate speeds the fuel-ignition requirements were essentially proportional. Attention should be called to the rapid increase in the amount of fuel consumed and to the exhaust smoke emitted when using fuels of cetane numbers below the critical value at the speed considered. Operation on fuels of such low cetane numbers is essentially impossible as severe misfiring occurs. As an illustration of the constancy of this engine the results of tests, carried out approximately eight months previous to the time at which the ignition-quality requirements were determined, are shown with dotted lines.

The service tests so far considered were of relatively short duration, and additional tests were made to determine any influence of fuel-ignition quality on engine fouling that might occur during long periods of service. In order to simulate the most severe conditions to which engines of this type might be subjected, a log was made of a trip from San Francisco Bay to Reno, Nev., and return. This route traverses the Sacramento Valley in which very high temperatures are encountered and crosses a mountain pass at over 7000 ft. altitude. A schedule was prepared which included all the loads, speeds, manifold pressures corresponding to altitudes, stops, and periods of over-running that would be encountered, and the engine was run in the laboratory in accordance therewith. This cycle was repeated a sufficient number of times to build a mileage of over 4000 miles per test, and fuels of varying ignition qualities were run. At the conclusion of each test the engine was completely dismantled for inspection, and it was found that no change in condition was traceable to the quality of the fuel.

All of the tests made on this engine demonstrated conclusively that, providing the ignition quality of the fuel is above a certain minimum value, no differentiation between fuels can be found. It is obvious, therefore, that correlation between laboratory tests and service performance in engines of the type represented by R.D. 1008 is impossible.

In Fig. 10 the results of some constant-speed tests, made on engine R.D. 1393 at 1200 r.p.m., are shown in which the same 40- and 60-cetane fuels previously mentioned were used. It will be noted that in these tests the same degree of exhaust smoke was obtained with both fuels, but the fuel consumption was lower throughout the load range when using the 60-cetane fuel. The 60-cetane fuel developed a slightly higher maximum power and knocked less severely than did the 40-cetane fuel. The close agreement in the data obtained when testing the two fuels, as well as the rather abnormally severe knock developed, suggested the possibility of improving the performance of the unit by slightly altering some of the mechanical adjustments set by the manufacturer. The injection timing was therefore altered slightly but beyond the range provided by the manufacturer, and the tests repeated. The data thus obtained are shown in Fig. 11. It will be noted that the performance on both fuels was essentially the same under these altered conditions. Attention is called, however, to the fuel consumptions, maximum powers, and smoke densities, all of which were materially better than obtained with either fuel when using the manufacturer's adjustments. Knocking was also materially reduced.

The data presented show that this engine rates fuels in the normal commercial range so nearly alike that correlation between service tests and laboratory ratings is extremely difficult. The data also show that a difference between fuels may be apparent rather than real and that even a minor engine adjustment can affect materially the results obtained.

It will be obvious that in a situation such as this no correla-

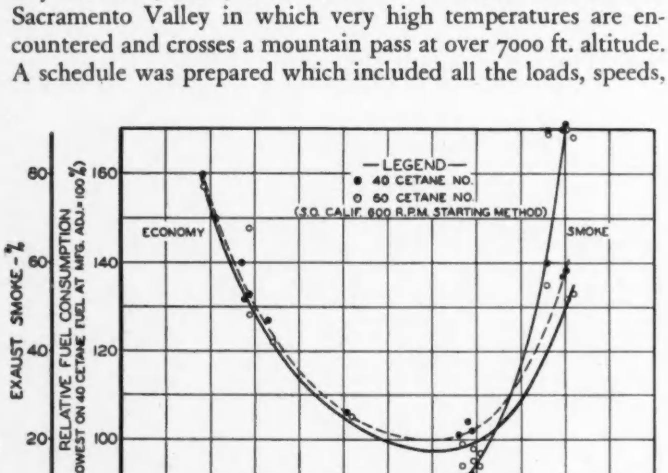


Fig. 10—Performance of Engine R.D.-1393

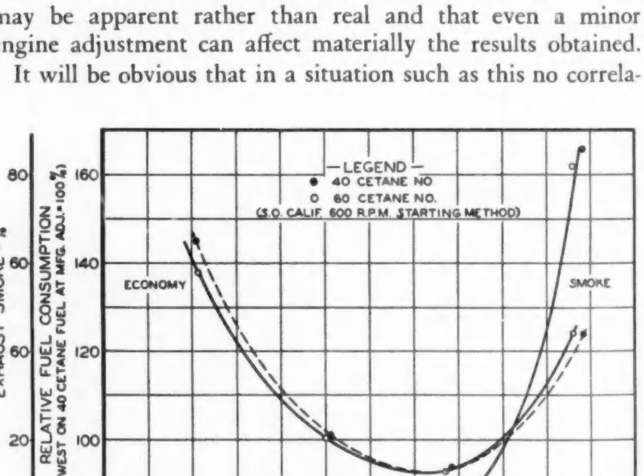


Fig. 11—Performance of Engine R.D.-1393 (Injection Readjusted)

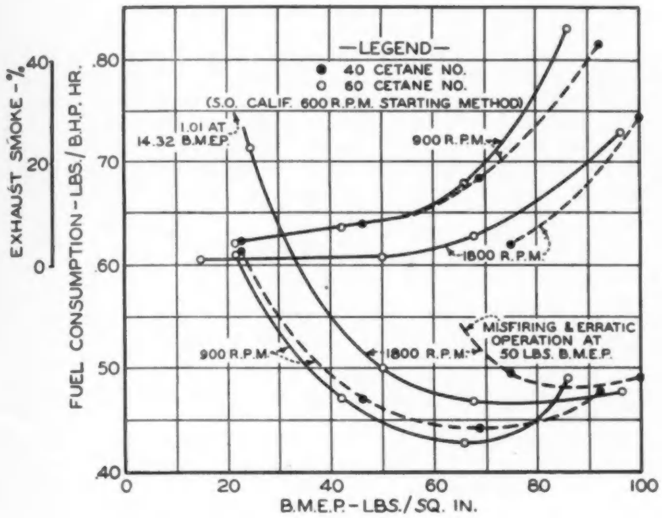


Fig. 12—Performance of Engine R.D.-1394

tion can exist between the laboratory rating of fuels and their service behavior under the various conditions likely to be encountered.

The same 40- and 60-cetane fuels were tested also in engine R.D. 1394. Results of some tests at 900 and 1800 r.p.m. are shown in Fig. 12. This engine apparently has very peculiar combustion characteristics which are not completely shown by the data presented. The exhaust smoke when using the 40-cetane fuel was, if anything, less at both speeds and all loads than when using the 60-cetane fuel. At 900 r.p.m. the fuel consumption was lower with the 60-cetane fuel at all b.m.e.p. values below 78 lb. per sq. in., while above this load the 40-cetane fuel was superior. The maximum power was also greater with the low cetane fuel. When the speed was raised to 1800 r.p.m., the 40-cetane fuel could not be run at even moderately reduced loads as misfiring occurred consistently; whereas some semblance of smooth running was obtained with the 60-cetane fuel at all loads.

Considerable difficulty was encountered in maintaining the coupling between the engine and the dynamometer. Its size was more than ample for transmitting the full torque of the engine, but failures continued. An investigation revealed that, even when running on the high cetane number fuel, combustion was erratic except over a very narrow range of brake mean effective pressures. Actually at high speeds and loads—above those shown in Fig. 12—smoother operation was obtained with the 40- than with the 60-cetane number fuel.

It appears that this engine is incorrectly adjusted, although in accordance with the manufacturer's recommendations, and further tests are contemplated. It may be, however, that the difficulty lies in the design and can only be corrected by structural changes.

Correlation between the results obtained on this engine and some form of laboratory test may be possible because of its apparently critical nature. However, an attempted correlation is not believed justified in view of the operating difficulties noted even with the 60-cetane fuel. It is doubtful that the manufacturer will continue to market engines requiring fuels of over 60-cetane number, by any method of laboratory test.

It may be concluded from the material presented that the ignition-quality determination of a fuel may be influenced greatly by changes in operating conditions. Service tests in commercial engines have shown a like influence of operating conditions and engine design on the performance of fuels.

The results show that service engines have distinct minimum requirements for fuel-ignition quality; that the minimum quality is different under different operating conditions; and that no essential difference in the performance of fuels can be noted providing the minimum ignition quality is exceeded. For all practical purposes, therefore, no correlation appears possible between the laboratory rating of fuels and their service behavior.

Laboratory means of rating the ignition quality of Diesel fuels appear of most importance to the engine builder, to be used by him as a guide in procuring fuels for development work, rather than as an index of the relative performance of different fuels in any given engine.

Discussion

Penn State Method Believed Faster and More Representative

—P. H. Schweitzer

Associate Professor, Pennsylvania State College

THIS is a good controversial paper. The Standard Oil of Calif. starting method for rating of Diesel fuels is similar to the Penn State method inasmuch as it eliminates bracketing in favor of calibration curves, and also as it expresses the rating in cetane numbers. It differs from the latter method in using a motored engine rather than a running engine and in using the compression pressure as variable in place of the compression ratio. I am naturally in favor of eliminating the laborious bracketing and in expressing the rating uniformly in terms of cetane number.

The use of compression pressure in place of compression ratio has the merit that it minimizes the effect of the barometric pressure. One could have that feature without the necessity of using a sensitive accurate high-pressure gage, which is expensive, if the intake-air pressure were read and kept constant by slightly throttling the intake air, and by interposing a small receiver between the adjustable throttle and the suction pipe of the engine.

The starting method as perfected by the author is reproducible and fairly convenient. I doubt that it is as fast as the Penn State method which permits testing conveniently seven to eight fuels in an hour, as stated in the paper of which the writer is a co-author. However, the decisive factor is which of the two methods is more representative.

As we have shown, the starting method correlates remarkably well with our fixed ignition lag method. Appreciable divergencies were sometimes noted with fuels of high viscosities. These fuels seemed to be appreciated by the starting method. The slow evaporation of such fuels may be the explanation of the divergency. Suppose fuels *A* and *B* ignite at the same temperature if the time lag is sufficiently long so that either of them has time to evaporate partially. However, fuel *A* being more volatile, with a short ignition lag of 18 deg., it will show up better than *B*. Therefore the starting test, where the ignition lag is long (about 180 deg.), would appreciate fuel *B* or depreciate fuel *A*, as compared with the delay method.

A study of the viscosities and initial boiling points of the cetane blends as well as those of the test fuels may be of interest.

When the starting method gives different rating from the delay method, I am inclined to attach more significance to the latter method as being more representative. The starting tests are not even entirely representative of the starting conditions of service engines as the jacket, cooling-water, and lubricating-oil temperatures are too high.

The ionization-gap ignition indicator is believed to be satisfactory to indicate whether firing has occurred or not. It is considered by Holfelder[a] unsuitable to indicate the instant of the ignition. Will the author state what method he used to determine the ignition lags shown in Fig. 5? Curves plotted from our data are much steeper. They do not flatten

[a] See *Vereines Deutscher Ingenieure-Forschungsheft* No. 374, 1935.

out at high compression ratios, and even the 60-cetane fuel shoots straight up between 11 and 12 compression ratios (using the comet-head C.F.R. engine). According to the curves of the author the difference in ignition lag between 40- and 60-cetane fuels is insignificant at 16 compression ratio, and the ignition lag changes negligibly between 15 and 16 compression ratio. If the author's curves are correct, the delay method is unsuitable to rate high-cetane Diesel fuels at normal compression ratios, but our tests fail to support these data.

The tests on service engines as carried out by the author are very useful and should be encouraged. His results, however, mostly contradict the results obtained by Boerlage and Broeze[b], Joachim[c], and the Naval Experiment Station[d]. Further confirmation or disapproval of the author's results is awaited with interest.

Correlation of Laboratory and Service Ratings Reported

—W. G. Ainsley
Sinclair Refining Co.

Our work has not shown such definite minimum cetane requirements as indicated by Fig. 9. The improvement in performance does tend to decrease with higher cetane number fuels, but a sharp break in the curve was not noted. Improvement as shown by reduced knock, cooler exhaust, and lower fuel consumption continues up to 74-cetane number on the commercial engines tested.

The correlation of laboratory cetane numbers with correctly adjusted service engines does not seem to be impossible. Several commercial engines have been used for fuel testing in our laboratory, and the correlation with the single-cylinder test unit has been most satisfactory.

Author's Experience with Nozzles and Adjustment Confirmed

—P. E. Biggar
Consulting Engineer
Toronto, Ont., Canada

MR. MACGREGOR'S paper is both timely and interesting since it emphasizes that oil fuel characteristics are only of value in so far as they relate to operating conditions. May I quarrel, however, with his Fig. 1? He shows that there exists a large proportion of "pre-combustion"-chamber engines in Britain; does he not mean "ante-chamber"? As far as I know there is only one precombustion-chamber engine built in Britain and that is made under German license. This may seem a very small point, but there is in America a very distinct tendency to mix up these two types, to the confusion of all concerned.

Incidentally, it might be of interest to oil refiners to mention the numbers produced. Although there are only two British manufacturers of any importance producing direct-injection engines, Gardner and Leyland, they obtain about two-thirds of the market between them. I know that this is contrary to American opinion, but it happens to be the case.

Mr. MacGregor's remarks on the poor starting qualities of open nozzles are of interest. In spite of the obvious advantages of this type of nozzle, we had to abandon its use in our truck engines about seven years ago for this very reason. On the other hand, it must be admitted that the starting of the Junkers opposed-piston engines, with their very high compression ratios and excellent combustion-chamber proportions, is very good indeed, although the nozzle contains no valves whatever.

Finally, Mr. MacGregor has something to say about the mechanical adjustments set by the manufacturer. He mentions no names, but one may judge that he was using an antechamber engine and that the adjustment he found at fault was the injection timing. In our experience there are two alternatives: either the timing must be wear-proof and tamper-proof (one manufacturer saws off the setscrew heads), or the combustion chamber must not mind the injection timing to within about 3 deg. either way.

One engine with which I am especially familiar goes to sleep if the injection is much retarded and knocks lustily if the injection is too much advanced. Incidentally, the final standard timing as well as the standard output of the fuel pump, with the control against the maximum delivery stop, were both fixed as a result of road tests by the Road Test Department, not by bench tests. The latter setting varies according to the type of chassis in which the engine is installed, owing to the varying conditions of load, normal speed and, whisper it not, the position of the exhaust tail-pipe underneath the body.

[b] See S.A.E. TRANSACTIONS, July, 1932, pp. 283-293; "Ignition Quality of Diesel Fuels as Expressed in Cetene Numbers", by G. D. Boerlage and J. J. Broeze.
[c] See Diesel Power, May, 1935, pp. 283-290; "The Characteristics of Diesel Fuel Oils", by W. F. Joachim.
[d] Report No. 6395-B, *Not Published*, Engineering Experiment Station, U. S. Naval Academy, Annapolis, Md.

What Variable Speed Transmissions Must Do

WE all know that the mechanical variable speed transmission has, for years, supplied a leading chapter in those intriguing books on "What to Invent". As a consequence inventors by the hundreds all over the world, most of them without much previous experience in transmission design, have tackled the problem, but so far without much evident success, since the only devices in general use today use gearing layouts that have been in the text books for over half a century.

The reason is not hard to find. The problem seems to be one of mathematics rather than mechanism—calculation rather than merely ingenuity. Failure to recognize this has led to the waste of hundreds of thousands of dollars that could have been avoided by a closer study of the figures.

It has often been said that a problem correctly stated is largely solved. Obviously the requirements for a variable speed transmission differ with the various applications so that the same general type of design can scarcely be expected to fill every job. The need in an automobile, for example, is quite different from that in an industrial machine. In most cases, however, a transmission is definitely wanted which will do the following:

1. Supply a compact connection between the desired prime mover and the shaft to be driven.
2. Deliver an infinite number of speeds over the desired range including, if needed, speeds from maximum direct, through zero, to an equal maximum speed in reverse.
3. Deliver the torque required plus ample reserve throughout the speed range.
4. Require minimum power to effect the speed change, under load, through any desired type of control, manual or automatic, remote or at the machine.
5. Deliver a continuous, non-pulsating flow of power at all speeds.
6. Maintain the delivered speed within close limits of regulation, independent of load, ambient temperature, atmospheric conditions, etc.
7. Provide a high efficiency with minimum frictional loss and heat.
8. Be inherently free from overload failure.
9. Insure durability, with infrequent need for maintenance or replacement, such maintenance being within the facilities of the ordinary user.
10. Accomplish these things in a simple construction, easily assembled and available at reasonable cost.

Excerpt from the paper "Mechanical Variable Speed Transmissions" presented at the Milwaukee Section Meeting, Dec. 9, 1935, by Louis A. Graham, sales manager, Falk Corp.

Report of the Volunteer Group for Compression-Ignition Fuel Research

By T. B. Rendel*
Chairman

ADOPTION of cetane-number scale and primary and secondary reference fuels, calibration of secondary reference fuels agreed upon, test procedure, and results of tests comprise the important points stressed in the second report of the Volunteer Group for Compression-Ignition Fuel Research.

Cetane number, which is the percentage of cetane in alpha methylnaphthalene that matches the ignition quality of the samples under test, has been adopted by the Group as the standard method for reporting results. For actual use in routine testing, suitable secondary reference fuels are available: a high-cetane fuel from the Shell Petroleum Corp., and a commercial grade of methylnaphthalene for the low-cetane fuel. A calibration curve of the secondary reference fuels in terms of the primary standards is included.

The method of test used is known as the delay method and involves matching the ignition delay determined on the C.F.R. high-turbulent-head Diesel engine by a suitable bouncing-pin apparatus, with the ignition delay of cetane and alpha methylnaphthalene. Complete details of the method of test are given as an appendix to the report.

Results of a series of cooperative tests showed surprisingly good agreement among the various laboratories. The grand average deviation for the nine samples being of the order of $\pm 1\frac{1}{2}$ cetane numbers. Alternative methods of test are discussed, in particular a series of tests involving the use of the critical compression ratio method with a special interval timing-control device. Results of these tests do not show such good agreement among the laboratories, but the average results obtained agree well with the average results obtained by the delay method. This agreement is encouraging from the point of view of correlation with service results, and in connection with the validity of the test.

AT the January, 1935, meeting of this body, a small group known as the Volunteer Group for C. I. Fuel Research was privileged to present its progress report dealing with probable methods of measuring the ignition quality of Diesel fuel[1]. During the past year interest in this problem has continued, and the committee has been very active in its endeavors to investigate various means of measuring this quality. It now has the honor to present its second report incorporating:

(a) A suggested tentative procedure for operating the modified C.F.R. engine.

(b) A recommendation as to the use of primary reference fuels and secondary reference fuels.

(c) The results of a series of cooperative tests on the measurement of ignition quality using nine different types of Diesel fuels.

[This report was presented at the Annual Meeting of the Society, Detroit, Jan. 14, 1936.]

* Director, motor test laboratory, Shell Petroleum Corp.

[1] See S.A.E. TRANSACTIONS, June, 1935, pp. 206-209; "Progress Report of Volunteer Group for C. I. Fuel Research", by T. B. Rendel.

The present membership of the committee is as follows:

T. B. Rendel, chairman	Shell Petroleum Corp.
C. H. Baxley, secretary	Sinclair Refining Co.
W. G. Ainsley	Sinclair Refining Co.
Clifford Banta	E. I. du Pont de Nemours
D. P. Barnard	Standard Oil Co. of Ind.
A. E. Becker	Standard Oil Development Co.
T. A. Boyd	General Motors Corp.
H. K. Cummings	National Bureau of Standards
W. H. Hubner	Universal Oil Products Co.
J. R. Sabina	Atlantic Refining Co.
L. C. Lichty	Department of Engineering, Yale Univ.
Neil MacCoull	The Texas Co.
J. R. MacGregor	Standard Oil Co. of Calif.
A. W. Pope, Jr.	Waukesha Motor Co.
C. H. Schlesman	Socony Vacuum Oil Co.

It will be recalled that the program of the committee, as outlined last year, called for working out detailed design changes and suitable operating technique for measuring the relative delay periods and critical compression ratios of different fuels, with a view to improving the reproducibility and simplicity of operation of a modified C.F.R. engine fitted with a special cylinder-head giving a variable compression ratio and a high degree of turbulence. It was desired to find also a suitable scale for expressing ignition quality, and to consider other physical and chemical methods of rating Diesel fuels. This program has been tackled by the committee during the past year with considerable success.

Modifications of Engine and Apparatus

In view of the greater promise of more significant results when working with ignition delays more nearly approximating those obtained in actual service, the Group concentrated first on the measurement of ignition quality by the "delay" method, that is, a method of comparing the actual ignition delay of the fuel under test in a running engine with the ignition delay of mixtures of suitably calibrated reference fuels. In working out this delay method, two troubles were most prominent: the first was connected with the steadiness of fuel injection timing, and the second with the adjusting of the bouncing pin. During the first half of 1935, therefore, efforts were concentrated on making a number of detailed improvements in the high-turbulence C.F.R. engine, principally on the fuel-injection system and bouncing-pin set-up.

The difficulties encountered in obtaining a steady injection appeared to be due largely to air locks in the fuel line and were overcome to a certain extent by redesigning the fuel system and eliminating, as far as possible, any place where an air bubble could be formed; this improvement applied particularly to the suction-side connections to the fuel pump. Further improvement was obtained by the use of a larger diameter fuel-delivery pipe between the pump and injector valves. It also was necessary to modify slightly the method of recording the timing of the fuel-injection valve. In the original instance this recording was done by "breaking" a set of contact points on the fuel valve, thus inducing a current in a neon tube mounted in a protractor on the end of the crankshaft. By rearranging the circuit so that the current flowed when the points made contact, arcing troubles were eliminated and steadier readings of the fuel-valve timing were obtained.

Another small change in this connection was made in the drive of make-and-break contact points operated in conjunction with the bouncing pin. It will be remembered that in the delay method the ignition delay is measured by means of a modified bouncing pin and a make-and-break contact timed to make the contact at the instant of fuel injection. In the original set-up, this make-and-break contact was driven from the end of the fuel-pump shaft and, consequently, the fuel-pump timing could not be varied independently of the make-and-break contact. This arrangement was troublesome at times and, in order to overcome the difficulty, the make-and-break contact was mounted on the tachometer drive shaft with the result that any variation in fuel-pump timing could be adjusted without readjusting the make-and-break contact. Fig. 1 shows the present set-up in diagrammatic form.

Table I—Properties of Cetane and Alpha Methylnaphthalene

	Cetane	Alpha Methylnaphthalene
Specific Gravity at 60/60 deg. fahr.	0.775	1.025
Boiling Range, deg. fahr.	544.1-553	469.6
Freezing Point, deg. fahr.	61.5	−7.6
Iodine Number	Nil	.....

Difficulties with the adjustment of the bouncing pin were largely overcome with practice without further changes in design. A very considerable amount of help was given in this direction by a visit from the Waukesha Motor Co.'s engineer to each of the cooperating laboratories in turn, although it must be admitted that further improvements will have to be investigated before complete satisfaction is obtained. By these visits the Group was also able to insure that, before starting a series of tests, every member was using the same procedure and the same set-up down to the smallest detail.

Tentative Standard Procedure

As a result of the Waukesha engineer's visits and of the experience of each member of the Group, it was found possible to draw up a tentative standard procedure which could be used in carrying out a series of cooperative check tests among the various members of the Group. Appendix A outlines this procedure, including the details of test technique, and is self-explanatory. Using this procedure, an operator with reasonable experience can rate six to eight samples a day if no difficulty occurs causing variations in bouncing-pin and injector operation. There are, however, some points that might be brought out in connection with difficulties in obtaining fuel ratings by the delay method:

(1) The engine should be dismantled for inspection and cleaning at about 50-hr. intervals.

(2) The injector must be kept clean, the actual hours of operation between cleanings being dependent entirely on the quality of fuels being rated. It is suggested that daily inspection is advisable.

(3) Ordinarily, little difficulty with air-locking will occur if the precautions outlined in the procedure are followed carefully. If air-locking or irregular injection occurs, it is sometimes necessary to shut down the engine, flush the fuel system, and clean the injector before satisfactory operation can be obtained again.

(4) The bouncing-pin adjustment can be made quite readily after a little experience with the equipment, and changes in setting can be prevented by obtaining the best setting originally. The sensitivity of the bouncing pin is somewhat variable, ranging from about one division per

cetane number for 75-cetane-number fuels to four divisions per cetane number for 20-cetane-number fuels.

Primary Reference Fuels

Another important aspect of the work of the Volunteer Group was the selection of a suitable scale for expressing ignition quality and the development of suitable primary reference fuels. For some time past, the "cetene-number" scale using mixtures of cetene and alpha methylnaphthalene, originally proposed by Boerlage and Broeze, has been more or less generally adopted. It is the alpha isomer of cetene ($C_{16}H_{32}$), an unsaturated hydrocarbon of the ethylene series, that is desired. However, it was found that successive batches of cetene, produced by various laboratories from different sources and of supposedly similar properties, apparently did not always have the same ignition quality. This confusion is thought to be due to the fact that the position of the double bond of cetene may shift during production thus giving any one of the various isomers, each having a different ignition quality.

As a result of cooperative work with the E. I. du Pont de Nemours & Co., it was decided to investigate cetane ($C_{16}H_{34}$, normal hexadecane), a straight chain hydrocarbon without the double bond of cetene. Cetane is a pure compound, inherently stable, and can be reproduced readily. The ignition quality of cetane is somewhat higher than cetene; and to date this fuel has proved quite satisfactory as a primary reference fuel. Cetane is obtainable at approximately $35 per gal. from the E. I. du Pont de Nemours & Co., Organic Chemicals Department, Wilmington, Del. Table I gives the properties of cetane.

Alpha methylnaphthalene ($C_{11}H_{10}$), a pure aromatic hydrocarbon, has been found a satisfactory primary standard low-reference fuel. It can be obtained from the Reilly Tar & Chemical Co., Indianapolis, Ind., at approximately $6 per gal. Table I gives the properties of alpha methylnaphthalene.

The foregoing primary reference fuels have been adopted by the Volunteer Group, and all results are expressed in terms of cetane numbers. The cetane number of a fuel is the percentage of cetane in admixture with alpha methylnaphthalene that matches the ignition quality of the sample.

Secondary Reference Fuels

Due to the cost of primary reference fuels, it was found necessary to consider the adoption of secondary reference fuels

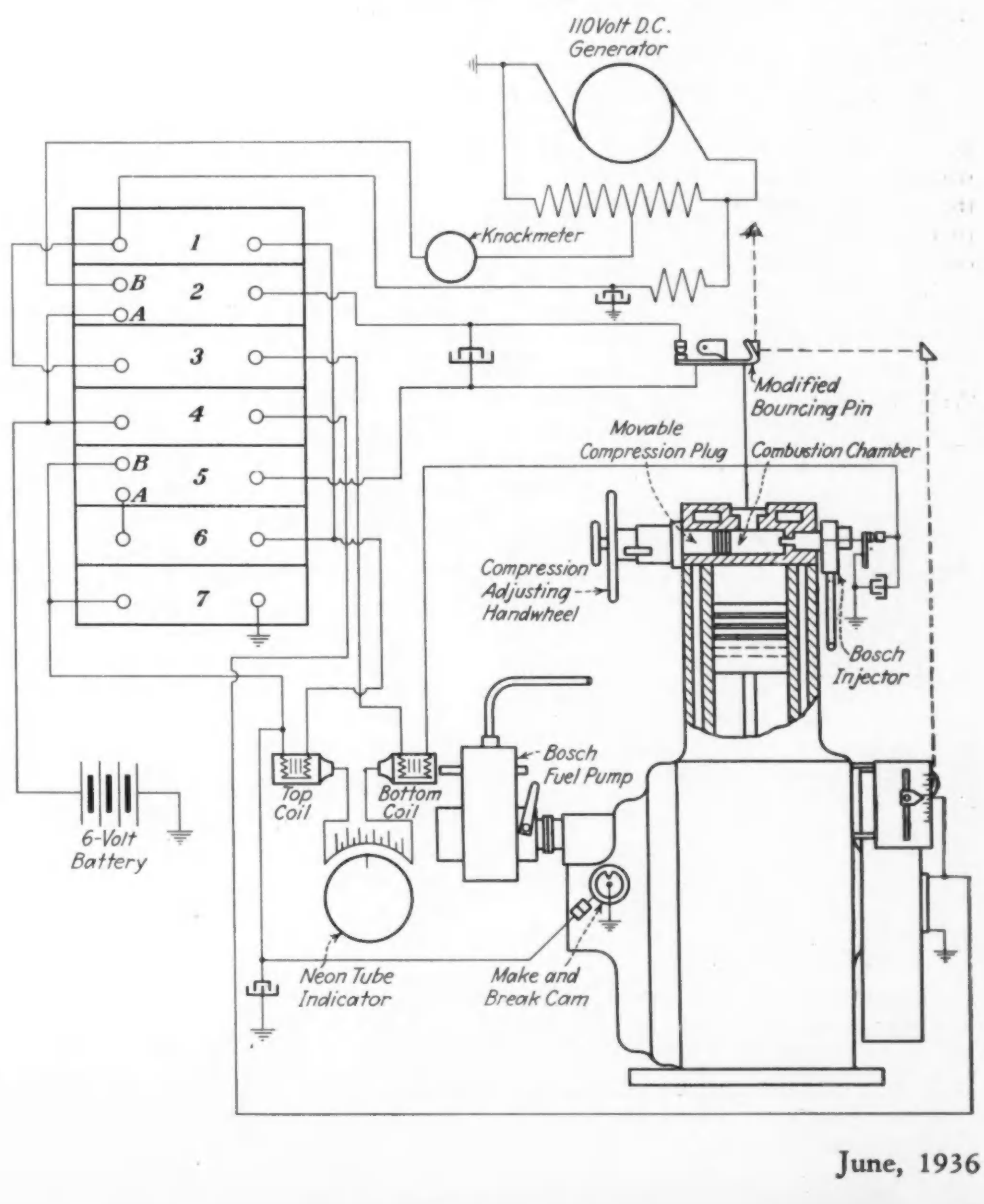


Fig. 1—Modified Circuit for Delay Method

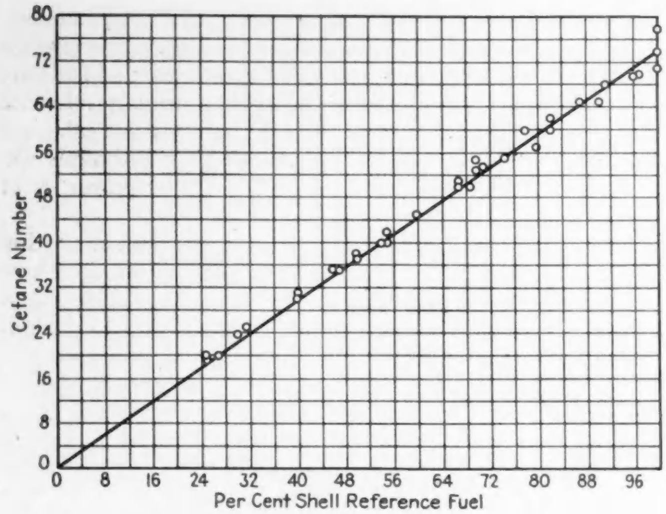


Fig. 2—Calibration of Shell Secondary Reference Fuel Against Mixtures of Cetane and Methylnaphthalene

in their place. A secondary high-reference fuel, used in place of cetane, can be obtained from the Shell Petroleum Corp., Wood River, Ill., at approximately $0.80 per gal. in 5- or 50-gal. lots. This material is a straight-run gas oil from a crude obtained from a small field in southern Illinois. The properties of this fuel are shown in Table II.

Commercial methylnaphthalene (a mixture of alpha and beta methylnaphthalene) is also obtainable from the Reilly Tar & Chemical Co., at approximately $2 per gal. This commercial grade has an ignition quality that closely approximates that of pure alpha methylnaphthalene, and has proved entirely suitable as a secondary reference fuel. The properties of this fuel are shown in Table II.

Calibration of the Shell secondary reference fuel against mixtures of cetane and methylnaphthalene by the delay method of rating according to the attached procedure is given in Fig. 2. This curve was prepared by several members of the Volunteer Group and is, therefore, an average of several engines. As in the practice of octane-number testing, it has been found that this method is perhaps the most accurate means of calibrating secondary reference fuels against primary reference fuels, and it will be noted that there is a very satisfactory agreement among the different laboratories, deviations from the average line being remarkably small considering the amount of testing that has been done on these engines.

Table II—Properties of Shell High-Cetane Secondary Reference Fuel and Commercial Methylnaphthalene

Shell High-Cetane Secondary Reference Fuel	
Gravity, deg. A. P. I.	42.3
Flash Point, Open Cup, deg. fahr.	180
Fire Point, Open Cup, deg. fahr.	215
Pour Point, deg. fahr.	15
Bottom Sediment and Water, per cent	Trace
Viscosity, Saybolt Universal at 100 deg. fahr., sec.	37.5
Conradson Carbon, per cent	0.02
Sulphur, per cent	0.34
Ash, per cent	Less than 0.01
Cetane Number (Delay method)	74
A. S. T. M. Distillation	
Initial Boiling Point, deg. fahr.	362
10 per cent off, deg. fahr.	443
20 " " " " "	470
30 " " " " "	490
40 " " " " "	508
50 " " " " "	524
60 " " " " "	541
70 " " " " "	560
80 " " " " "	584
90 " " " " "	622
End Point, deg. fahr.	698
Properties of Commercial Methylnaphthalene	
Specific Gravity at 60/60 deg. fahr.	1.011
Boiling Range, deg. fahr.	449.8–473.0
Freezing Point, deg. fahr.	51

Cooperative Tests

After agreeing upon the details of operation and questions of primary and secondary reference fuels, the committee decided to circulate a set of nine samples from various sources to each member for the purpose of rating these samples by the delay method and by any other method that might be considered advisable, such as the critical-compression-ratio method, in order to check the reproducibility among different engines with different methods. A brief description of the circulated samples and their physical properties together with the laboratories supplying them are given in Appendix B.

Table III—Volunteer Group Cooperative Diesel Fuel Tests—Delay Method—Per Cent Shell Reference Fuel

Laboratory	R	S	T	U	V	W	X	Y	Z
1	43	42	52	54	51	69	65	83	92
2	35	42	51	43	54	71	68	79	91
3	34	39	47	49	48	69	72	79	94
4	41	42	53	55	50	71	73	85	93
5	38	41	52	50	47	68	64	81	93
6	42	41	53	52	52	69	70	84	93
7	41	43	57	53	50	67	74	84	93
8	40	42	54	53	51	72	66	84	93
9	40	40	56	48	49	71	69	82	95
10	41	42	56	52	54	70	66	83	91
11	41	41	55	50	50	71	67	82	91
12	43	39	57	49	48	70	74	79	93
13	39.5	42.5	52.0	52.0	52.5	70.0	66.5	86.5	95.0
Average	40.0	41.2	53.6	50.8	50.7	69.9	68.8	82.3	92.8
Average Deviation	2.0	1.0	2.3	2.4	1.8	1.1	2.9	1.8	0.9
Maximum Deviation	+3.0	+1.8	+3.4	+4.2	+3.3	+2.1	+5.2	+4.1	+2.2
	−6.0	−2.2	−6.6	−7.8	−3.7	−2.9	−4.8	−3.3	−1.8

Table III shows the results obtained by the delay method expressed in terms of secondary reference fuels. Fig. 3 shows the average deviations for each laboratory in graphical form. These deviations are of the same order as the deviations noted on the calibration curve and, considering the short time this method has been in use, show remarkably good agreement. The grand average for the nine samples among the thirteen laboratories is 1.8 per cent Shell reference fuel. The results, converted into cetane numbers by means of the average calibration curve shown in Fig. 2, are shown in Table IV; the average deviation, in this case, being 1.3 cetane numbers. The maximum spreads are on the whole quite reasonable. The results show that the delay method (expressing the results in terms of cetane numbers), is certainly worthy of serious consideration for adoption as a tentative standard for measuring ignition quality.

Future Program

In regard to a future program for the committee there is, of course, one outstanding matter to be investigated, and that is the question of determining the validity and significance of this method of measuring ignition quality. It is also neces-

sary, however, to consider more thoroughly other possible methods of measuring ignition quality and, in particular, the critical-compression-ratio method. To some extent, the Volunteer Group has investigated this method in the series of tests reported here. A number of member laboratories have rated the cooperative set of samples by the critical-compression-ratio method suggested by Pope and Murdock, but using a special interval timer developed by the Waukesha Motor Co. and the Standard Oil Co. of Calif. This interval-timing device overcomes many objections which were inherent in the original critical-compression-ratio method. One of the chief objections to the critical-compression-ratio method and one of the chief causes of incomplete combustion was the injection of fuel into the cylinder for 3 sec. before firing could take place. Not only was this fuel "cooked" during these 3 sec., causing carbon deposition on the nozzle and pistons, but it also seemed to involve the determination of a false critical compression ratio due to the fact that some reaction possibly occurred during the 3-sec. period, and that it was a product of this reaction that ignited rather than the fresh fuel injected into the cylinder. To overcome this difficulty, an interval-timing control was devised which allows only 2 shots of fuel every 30 engine cycles. The control mechanism consists of a cam-operated bypass valve in the injection line, designed so that it closes the bypass valve during 5 revolutions of the engine out of every 60. This arrangement permits selecting a timing position that will produce 2 injections of the fuel proper every 30 cycles with the engine operating at 900 r.p.m. The timer has the advantage of further simplifying the procedure and keeping the engine cleaner for a much longer period of time, with consequent improvement in the reproducibility of results. It does not, however, do away with the objection that the length of delay obtained when measuring critical compression ratios is far longer than that actually obtained under service conditions. Table V shows the results of eight different laboratories using the critical-compression-ratio method.

Table IV—Volunteer Group Cooperative Diesel Fuel Tests—Delay Method—Cetane Numbers from Table III and Average Calibration Curve (Fig. 2)

Laboratory	R	S	T	U	V	W	X	Y	Z
1	32	31	38.5	40	38	51	48	61.5	68
2	26	31	38	32	40	52.5	50.5	58.5	67
3	25	29	35	36.5	35.5	51	53	58.5	69.5
4	30.5	31	39.5	40.5	37	52.5	54	63	69
5	28	30.5	38.5	37	35	50	47.5	60	69
6	31	30.5	39.5	38.5	38.5	51	52	62	69
7	30.5	32	42	39.5	37	49	55	62	69
8	29.5	31	40	39.5	37.5	53	49	62	69
9	29.5	29.5	41.5	35.5	36.5	52.5	51	61	70.5
10	30.5	31	41.5	38.5	40	52	49	61.5	67
11	31	30.5	41.5	37	37	52.5	50.5	61	67
12	32	29	42	36.5	35.5	52	55	58.5	69
13	29.5	31	38.5	38.5	38.5	51.5	49.5	63.5	69.5
Average	29.6	30.5	39.7	37.7	37.4	51.6	51.1	61.1	68.7
Average Deviation	1.6	0.7	1.6	1.8	1.3	0.9	2.0	1.3	0.8
Maximum Deviation	+2.4	+1.5	+2.3	+2.8	+2.6	+1.4	+3.9	+2.4	+1.8
	−4.6	−1.5	−4.7	−5.7	−2.4	−2.6	−3.6	−2.6	−1.7

Table V—Volunteer Group Cooperative Diesel Fuel Tests—C.C.R. Method—Per Cent Shell Reference Fuel

Laboratory	R	S	T	U	V	W	X	Y	Z
1*	43	39	53	50	55	67	74	88	93
2	39	39	57	49	53	68	75	83	95
3†	47	44	62	56	59	70	64	86	91
4	41	42	52	57	59	67	61	74	94
5	38	43	51	49	52	62	65	78	84
6*	44	40	54	52	53	67	69	86	95
7	31	39	52	50	52	61	62	85	91
8	43	41	54	45	50	59	72	73	86
Average	41	41	54	51	54	65	68	82	91
Average Deviation	3.5	1.6	2.4	3.0	2.6	3.4	4.8	4.9	3.1
Maximum Deviation	+6	+3	+8	+6	+5	+5	+7	+6	+4
	−10	−2	−3	−6	−4	−6	−7	−9	−7

*Used 18 cc. per min. fuel quantity.
†Used 1250 lb. per sq. in. injection pressure.

It will be noted that the agreement among the eight laboratories is not quite as good as by the delay method, possibly due to lack of detail standardization, but that the average results agree very well with those obtained by the delay method. This agreement is important as, assuming the delay method results are valid in terms of actual engine operation because the ignition delays are somewhat nearer those obtained in actual practice, then the critical-compression-ratio results are also valid even though the length of the delay is somewhat extreme. Again, it is promising since, if two such radically different methods give the same results, it would seem that there will be less trouble in correlating the results with actual service conditions. Other methods of approximating the ignition qualities of Diesel fuels are available, such as the Diesel index developed by Fischer and Becker[2] or the viscosity-gravity constant of Moore and Kaye[3].

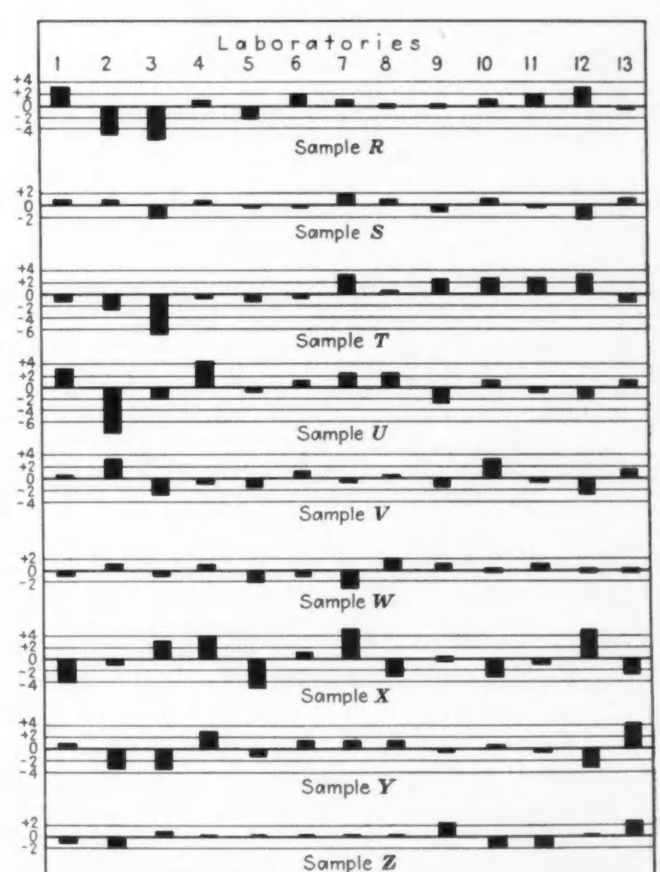


Fig. 3—Deviations from Average Results—Per Cent Shell Reference Fuel—Delay Method—Volunteer Group Cooperative Tests

[2] See S.A.E. TRANSACTIONS, October, 1934, pp. 376-384; "Suggested Index of Diesel Fuel Performance", by A. E. Becker and H. G. M. Fischer.
[3] See *The Oil and Gas Journal*, Nov. 15, 1934, pp. 108-111; "Practical Evaluation of the Ignition Characteristics of Diesel Fuel Oils", by C. C. Moore, Jr., and G. R. Kaye.

There is also the method sometimes used, which is to blend the sample with a high-octane-number gasoline and then to determine the octane number in the usual manner on a C.F.R. engine and, hence, determine the cetane number from a predetermined calibration curve. All these various methods appear to give reasonable correlation with actual engine results over the normal range of gas oils but are likely to be in error in certain cases and, consequently, it would seem best as a fundamental basis to come back to the actual determination of ignition quality in an engine.

Conclusion

Cetane number is the most suitable method for expressing ignition quality (considered apart from the significance and validity of the operating conditions used). The method of determining cetane number by the delay method in the modified C.F.R. Diesel engine with a high-turbulent head appears, at this time, to be the most satisfactory technique. It still requires further work on the method of registering the ignition delay and on steadying the fuel-injection timing as the present bouncing pin is sometimes difficult to keep in adjustment and results in delays in testing. However, in discussing the necessity for improved instrumentation and slowness at arriving at results, it might be recalled that an octane-number test after three years' development still requires about 45 min. and is still the basis of a very considerable amount of research for improved instrumentation and methods of operation. Adoption of cetane numbers and their method of determination, therefore, need not necessarily be delayed as a tentative standard until the high degree of perfection sometimes wished for is reached.

Appendix A

Tentative Standard Operating Conditions and Procedure for Delay Method of Rating Diesel Fuels on Waukesha High-Turbulence Diesel

OPERATING CONDITIONS

(1) Engine speed........... 900 r.p.m.
(2) Jacket temperature...... Constant within ±1 deg. fahr., limits 205 to 215 deg. fahr.
(3) Cooling liquid.......... Distilled water
(4) Crankcase lubricating oil. S.A.E. No. 30
(5) Oil pressure............ 20 to 25 lb. per sq. in.
(6) Valve clearances........ Intake, 0.008 in., cold; exhaust, 0.010 in., cold
(7) Injection advance....... 10 deg. before top dead-center
(8) Injection pressure....... 1500 lb. per sq. in. (opening pressure)
(9) Fuel quantity.......... 12.0 cc. per min.
(10) Inlet-air temperature... 150 deg. fahr.

PROCEDURE

(A) Starting and Stopping the Engine

While the engine is being turned over by the electric motor, the fuel bypass valve on the injector is closed and the compression ratio is increased until the engine begins to fire.

To stop the engine, the fuel bypass valve on the injector is opened and the electric motor is then switched off.

(B) Outline of Procedure

The cetane number of a fuel is ascertained by comparing the delay (as measured with the knockmeter) for the fuel with those for various blends of the reference fuels until two blends differing in delay by not more than the equivalent of eight cetane numbers are found, one of which has a longer delay and the other a shorter delay period than the sample.

(C) Injector Indicator Setting

(1) Loosen the contact spring carrier clamp nuts and adjust them until the spring leaf just touches the injector pin. Then set the clamp nuts to provide ½ turn initial tension on the spring.
(2) Adjust the gap between the contact points to 0.004 in.

(D) Bouncing-Pin Preliminary Static Setting

Make static bouncing-pin setting as follows:

(1) Set gap between pin and arm at 0.005 in. with gap adjusting screw.
(2) Bear down lightly on the end of the contact-arm spring so that the arm is held on its seat. Adjust the spring-tension screw until the screw just touches the spring. Then increase the tension by turning the screw down five notches.

(E) Final Compression-Ratio and Bouncing-Pin Adjustment

After the engine has reached equilibrium the compression-ratio and bouncing-pin setting at which an unknown fuel is rated are determined as follows:

(1) Adjust the compression ratio about two compression ratios above that at which definite misfiring occurs.
(2) With the engine firing, close the bouncing-pin gap between pin and arm by turning the adjustment screw up until two distinct lines appear ahead of the "bump" on the optical indicator diagram. (This setting indicates that the bouncing-pin arm is deflected by the compression pressure before combustion.)
(3) With the engine firing, increase the bouncing-pin gap between pin and arm by turning the adjustment screw down until the double line on the optical indicator just coincides with the base line. (This setting indicates that the bouncing-pin arm is not moved by compression pressure, but is deflected the moment compression pressure is exceeded by combustion.)
(4) Observe the angle at which combustion starts. The correct angle of combustion for making a rating is 1 deg. after top dead-center. Readjust the compression ratio until this condition is obtained.
(5) After a change in compression ratio, readjust the bouncing pin as outlined in (2) and (3) above.
(6) If the indicated angle of injection after the final bouncing-pin setting has shifted more than ½ deg., readjust the compression ratio and pin as outlined above.
(7) Check the regularity of the bouncing pin on the neon-tube indicator. If the angle of combustion fluctuates more than ±1 deg., adjust the bouncing-pin tension screw by trial until steady readings are obtained.

(F) Adjustment of Contact Breaker

The make-and-break points in the knockmeter circuit should be adjusted for an 8-deg. contact period, as determined

on the neon-tube indicator. This period can also be indicated on the knockmeter and should produce a reading of 80 to 100 on the scale when the generator voltage is 120 and the engine is not firing. The breaker timing should be adjusted to make contact approximately 2 deg. before top dead-center as indicated on the neon-tube indicator. Check this setting on the knockmeter with 120 generator voltage. A knockmeter reading of 50 should be obtained with the engine firing when combustion occurs at 1 deg. after top dead-center. Advance or retard the breaker until such a knockmeter reading is obtained.

(G) Cetane-Number Determination

An alternate series of knockmeter readings is taken on the test fuel and reference-fuel blends differing by 10 per cent. After changing from one fuel to the other, 5 min. must be allowed to insure the complete change-over since there is a comparatively large volume of fuel in the pump and line.

At least three alternate series of readings should be taken on each fuel and, if the average knockmeter reading of the fuel sample is higher than that of the reference-fuel blend, the test should be repeated with a blend containing decreased proportion of the high-cetane-number reference fuel. The test is continued in this manner until the knockmeter reading for the sample is definitely higher than one blend and lower than another blend of the reference fuels.

(H) Calculation

The exact rating of the fuel sample is obtained by interpolation from the knockmeter readings thus obtained and reported to the nearest whole number.

(I) Note

To obtain the best results the following precautions must be observed:

(1) *Clean* fuel must be used. It is suggested that the fuel be filtered through thin chamois leather into the fuel tanks.

(2) The fuel lines and fuel pump must be thoroughly flushed of air before starting the engine. After the engine is running, better results are obtained by switching quickly from one fuel to another ***without flushing the fuel pump,*** and allowing 5 min. for the change-over.

(3) When changing fuels in the tanks, it is very necessary to flush the line to the switch valve thoroughly until a solid fuel stream is obtained from the bleed drain.

(4) The fuel injection timing should be shown continually on the spark quadrant and any deviation from 10 deg. before top dead-center must be corrected before each knockmeter reading is taken.

Appendix B

Volunteer Group Cooperative Diesel Fuel Tests—Average Physical Properties of Samples

Sample	R	S	T	U	V	W	X	Y	Z
Gravity, deg. A. P. I.	36.1	19.7	34.0	23.1	28.8	29.4	45.5	40.7	41.3
Viscosity, Saybolt Universal at 100 deg. fahr., sec.	32	33	33	53	42	34	32	37	36
Aniline Cloud Point, deg. fahr.	126.2	73.7	119.2	131.5	134.8	124.6	152.4	175.0	172
Diesel Index	45.6	14.5	40.7	30.3	38.8	36.6	69.3	71.3	71.0
Flash Point (Pensky-Martens), deg. fahr.	125	197	187	174	227	188	124	185	178
Fire Point (Open Cup), deg. fahr.	135	215	205	245	260	215	140	230	225
Pour Point, deg. fahr.	−25	+18	−10	+2	−15	+2	B−26	+7	+7
Sulphur (Bomb), per cent	0.12	0.74	0.45	1.17	0.56	0.54	0.07	0.16	0.18
Ash, per cent, less than	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Carbon Residue, per cent	Less than 0.01	Less than 0.01	0.07	0.31	Less than 0.01	Less than 0.01	Less than 0.01	Less than 0.01	Less than 0.01
Initial Boiling Point, deg. fahr.	323	419	401	387	456	399	322	393	372
10 per cent recovery, deg. fahr.	355	449	429	482	501	446	364	474	459
20 " " " " "	356	455	438	518	514	457	380	494	482
30 " " " " "	377	459	444	554	528	465	396	506	496
40 " " " " "	385	463	451	585	542	473	414	520	508
50 " " " " "	396	466	461	622	552	582	430	532	518
60 " " " " "	404	470	472	654	565	495	447	547	529
70 " " " " "	416	477	480	688	577	517	465	562	541
80 " " " " "	427	493	504	708	594	548	483	581	560
90 " " " " "	448	558	537	740	615	597	505	614	599
Final Boiling Point, deg. fahr.	493	664	609	760+	655	683	549	667	694
Recovery, per cent	98.5	97.5	97.5	75.5	98	97.5	98.0	97.5	96.0
Residue and Loss, per cent	1.5	2.5	2.5	24.5	2.0	2.5	2.0	2.5	4.0

Composition, Source, and Supplier of Cooperative Test Fuels

Sample	Composition	Source	Supplier
R	Straight run	Southern Texas	Sinclair Refining Co.
S	40 per cent Shell reference fuel+ 60 per cent methylnaphthalene		Shell Petroleum Corp.
T	Cracked	Mid-Continent	Shell Petroleum Corp.
U	Cracked	Mid-Continent	Standard Oil Co. of N. J.
V		California	Standard Oil Co. of Calif.
W	68 per cent Shell reference fuel+ 32 per cent methylnaphthalene		Shell Petroleum Corp.
X	Straight run	Mid-Continent	Standard Oil Co. of N. J.
Y	Straight run	Pennsylvania	Standard Oil Co. of N. Y.
Z	Straight run	Michigan	Universal Oil Products

Discussion

Errors Due to Viscosity Variation Plotted

—W. G. Ainsley
Sinclair Refining Co.

THE Committee has experienced some difficulty in testing samples of a wide range of viscosities. An analysis was made of the delay method results reported in Mr. Rendel's paper and variation of error with viscosity seems sufficiently pronounced to be of interest.

The quantity,

$$\frac{\text{Absolute viscosity of sample}}{\text{Absolute viscosity of matching reference fuel,}}$$

has been taken as an indication of the variation in viscosity between the samples which are matched in the engine. This value was used as

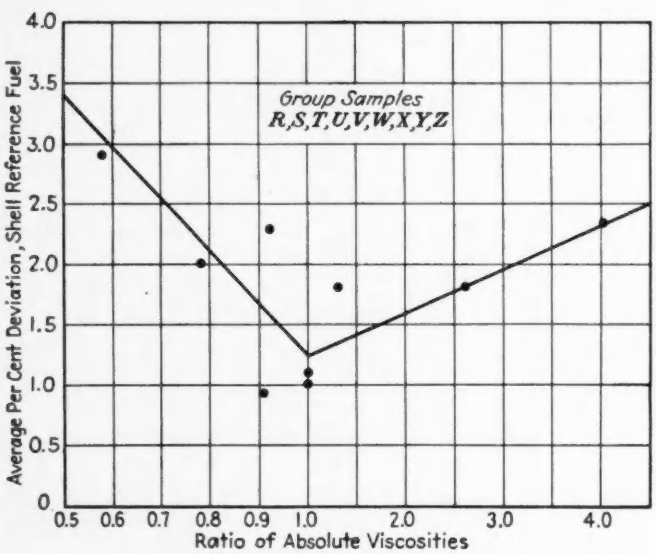


Fig. *A* (Ainsley Discussion)—Variation of Ratings with Viscosities

the abscissa in Fig. *A*, and the average per cent of deviation taken as the ordinate.

Due to the nature of the information available the curves shown are not very accurate, but we feel that the tendency is distinct enough to definitely indicate the approximate extent of the errors that are due to viscosity variation. The errors seem to be about equal to all other experimental errors when fuels of normal viscosity ranges are used, and the existence of this type of error emphasizes the need for a better injection system for the test unit.

Disadvantages of Bouncing Pin and Knockmeter Discussed

—Theodore B. Hetzel
The Pennsylvania State College

ANY test method that rates fuels by a measurement of the ignition lag depends on a constantly maintained time of injection, even if the current measured by the knockmeter were to embrace the entire ignition lag. We could not trace the inconstancy of injection to air lock, for no amount of line flushing, not even 25 lb. per sq. in. on the fuel supply, could eliminate fluctuation of the timing through the range of 1 deg. This fluctuation persisted even with the nozzle mounted directly on the pump. However, we did find that the cam-follower roller was slightly eccentric, and substitution of a more accurate roller reduced the spread of injection timing to ½ deg. Perhaps a mushroom-type follower would be better for this very exacting service.

At least five refineries have abandoned the bouncing pin for Diesel fuel testing, and even those who still use it admit that it is unsatisfactory in its present form. Why not discard it entirely? The answer probably lies in the desire to retain the knockmeter, although a circuit similar to the one used at Penn State could also be used to control the flow of current to a meter.

However, I feel that the knockmeter also is undesirable. Incidentally, it costs more than our complete ignition-lag-indicating equipment. Fuels should be tested only in a clean and properly operating engine and, if these conditions are met, an integrating device is not necessary. Moreover, misfiring, which can occur when the pump is flushed in changing fuels, increases the knockmeter reading to such an extent that a long wait is required to reestablish a steady reading. To avoid this difficulty the method of rating a fuel proposed by the Group involves 45 min. of waiting while the pump and tubing are purged of the fuels previously used. (See paragraphs G, Appendix A.) If the pump may be flushed the change-over takes about ½ min. per sample.

Our ratings of these same fuels, kindly supplied to us by Mr. Rendel, tend to be higher than the ratings obtained by the Group's method (except for the "catch" fuels *S* and *W* which we rate as 41.3 and 68.0 per cent Shell reference fuel, the true ratings being 40 and 68 per cent, respectively).

In conclusion I would like to ask the author why the air-inlet temperature was increased to 150 deg. fahr., and to state that we are in hearty agreement with all his conclusions.

Methods Proposed for Determining the Instant of Ignition

—K. J. De Juhasz
The Pennsylvania State College

MR. RENDEL stressed the need for investigating more thoroughly other possible methods of measuring ignition quality. In this connection a modification of the delay method which has been developed by the Socony-Vacuum Oil Co. may be mentioned. In this method a contactor mounted upon the injector body starts an electrical timing circuit at the instant at which fuel begins to enter the cylinder. A balanced diaphragm of the N.A.C.A. type is mounted into the cylinder head and is used to stop the electrical timer at the instant at which the combustion pressure exceeds the compression pressure by 75 lb. per sq. in. This method substitutes an arbitrarily adopted pressure difference for the arbitrarily adopted rate of pressure rise used in the Penn State method.

In order to do full justice to the name "ignition-delay method" it would be necessary to determine as accurately as possible the instant of ignition, that is, the crank angle at which the cylinder pressure begins to exceed the value that would exist if there were no ignition. The writer proposes the following method for the determination of this crank angle.

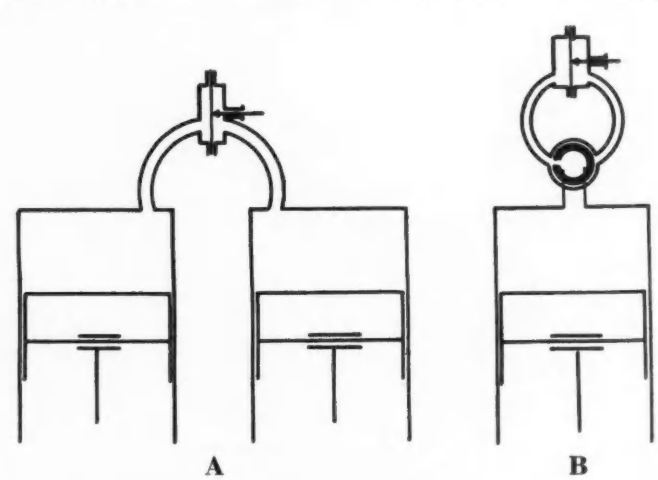


Fig. *A* (De Juhasz Discussion)—Proposed Two-Cylinder Test Engine

Fig. *B* (De Juhasz Discussion)—Proposed Modifications to Present One-Cylinder Test Engine

A two-cylinder test engine is used (Fig. *A*) with pistons moving in identical phase and with compression ratios kept identical by means of suitable interconnection between the compression-setting screw gears. Into one cylinder fuel is injected, into the other no fuel is injected; otherwise the conditions and operation in both cylinders are kept identical. A differential pressure gage (such as a balanced diaphragm) is connected to both the cylinders and indicates electrically the instant at which the pressure in the firing cylinder begins to exceed the pressure in the non-firing cylinder.

If the cost of building such a two-cylinder test unit is considered objectionable the method can be modified to suit the present one-cylinder test unit with only little alteration (Fig. *B*):

The test engine is operated, so to speak, on an eight-stroke cycle or double-four-cycle principle. Fuel injection occurs every even-numbered cycle, no fuel is injected in each odd-numbered cycle. The two sides of a differential pressure indicator (preferably of the balanced-diaphragm type) are brought into communication in alternate cycles with the engine cylinder. This arrangement can be accomplished by a sampling valve of short duration of opening, driven positively from the engine shaft. The phase of communication is altered until the differential pressure indicator registers a pressure difference.

In view of the great economic importance of accurate fuel rating, and of the none too satisfactory result of the rating methods hitherto used, the exploration of novel methods seems to be more than justified.

Sales Engineering Involves Cooperation—and Facts

THERE are some fundamental principles which can be applied to sales engineering. One is that personal contact between individuals is a very large factor in controlling business. It is becoming more and more important as time goes on. Many organizations find it necessary from year to year to increase their sales engineering staffs so that they will have someone more or less often come in contact with those who have to do with their business in the customer's organization.

Once a very successful sales engineer made the statement that it was a rule of his life never to write a letter when it was at all possible to see the man to whom the letter would have been written. This matter of personal contact has especially to do with the sales engineer getting into such relation with his customers that they will depend upon him implicitly for guidance in the matter of purchasing his company's apparatus. This is a principle which has not been well understood in some commercial circles. Some time ago I heard a purchaser make the remark that he was absolutely opposed to depending upon manufacturers of apparatus for information as to what he should purchase as best suited for his requirements. That man had not awakened to the full importance of present day engineering, because it is becoming more and more well understood from day to day that the best informed people in engineering are the manufacturers of apparatus, who can better guide a purchaser in ordering the proper material than the purchaser can do for himself. Therefore, the more completely a sales engineer can lead his customers to depend upon his organization for guidance in this way, the more completely he will have a permanent hold upon the business. Obviously, this can only be brought about by loyalty of purpose and sincere attention to all the details of business. To get his customer to depend upon him this way, he must set up the standard of work and conduct which will be on a very high plane.

The days of assertion, opinion and personality are passing. The time of the engineer is at hand. It is no longer a matter of parts, but of conditions and principles. Intelligent, effective cooperation can best be given by a careful detail of facts, an accurate analysis of conditions and a clear statement of what is proposed or objected to. The sales engineer who possesses the true spirit of cooperation will be careful not to reason from the general to the special, nor from the special to the general, nor from the special to the special. He will make sure that he has the facts, that these facts have a real relation to the matter in hand, that he is not unconsciously resorting to misleading statements, and lastly, after having assured himself of the foregoing, that the reasons he sets forth to his engineering department for certain changes or new devices are sufficient; for everything may be as he discovers it and yet there may be good and sufficient reasons for permitting things to remain as they are.

Cooperation on the part of the sales engineer in commercial and general engineering features and problems may be manifested in many ways, but must involve at least intimate knowledge of the problem in hand which covers conditions and limitations and possible means that may be employed to work it out. These alone are sufficient to cause reflection on his part and a conviction that the problem is sometimes not an easy one.

When cooperation takes the form of supplying information, it is imperative that great care be used, both in obtaining and transmitting it. In engineering matters, it is important that the sales engineer err on the side of supplying excessive rather than insufficient information to those in the home office. While conciseness is to be desired, particular effort in this direction may result in the information being obscure and open to misconstruction. The sales engineer should write or state the case so that if not understood, it cannot be misunderstood. It is difficult to contribute the cooperation intended if what is expressed is open to optional interpretation. Often through this misunderstanding, it may be thought that suggestions and recommendations have not received proper consideration, which in turn tends to discourage such efforts. Cooperation and cooperators are best served by information that is reliable, definite, accurate and complete. The sales engineer should remember that those at the home office are miles away from the place where the information was obtained. This means that it is necessary for him to solve the problem himself, or give those back home the kind of information that will permit them to put themselves in his place. One of the most embarrassing forms of cooperation is the expressing or offering of opinions. Opinions have their proper place, no doubt, but I have never found much use for them in evolving or designing air brakes. There should be no opinions where there is material for judgment or means for obtaining facts. This is all the more apparent when we consider that opinions are generally expressed against and seldom for a project. Perhaps this is significant.

Cooperation may be helped by not giving opinions as equivalent of facts, by not rehearsing observations as experiences, by not expressing doubts so as to convey the impression of final conviction, by not considering denial as being superior to affirmation, by not trying to convince oneself and others that a notion is equal to knowledge, and by not being sure that everything will fail because most things do.

Excerpts from the paper "Sales Engineering" presented at the Metropolitan Section Meeting, March 9, 1936, by Stephen Johnson, Jr., chief engineer, Bendix Westinghouse Automotive Air Brake Co.

Air-Cooled Radial Aircraft-Engine Performance Possibilities

By Raymond W. Young
Wright Aeronautical Corp.

DURING the past decade the general trend of aircraft-engine design has continued toward increased piston displacement, higher crankshaft speed, higher brake mean effective pressure, and improved materials.

These changes have had a marked influence on increasing the overall performance of the airplane by improving take-off, bettering climb, permitting higher cruising speeds at greater altitude, increasing periods between overhaul, and improving the reliability of the powerplant.

Although of secondary importance until quite recently, today fuel economy has become a major objective in both military and commercial operation.

Fuel consumption is a function, generally speaking, of engine design, of the properties of the fuel itself, and of the procedure for introducing and regulating the fuel-air mixture in the operation of the powerplant. Referring to engine design, lower specific fuel consumption may be obtained by careful attention to effective cooling of the combustion chamber and piston with optimum compression ratio for the fuel characteristics, and to good distribution and turbulence with efficient supercharging.

Ethylized fuels of high-knock rating have been a very important factor in the recent improvement of aircraft-engine performance. Despite means for regulating the fuel-air ratio to compensate for altitude or to obtain fuel economy, results have not measured up to the standards of economy desired. A major difficulty in the attainment of optimum fuel economy is described as the lack of some instrument which would definitely indicate to the pilot the immediate effect of manipulating the mixture control, and also would regulate the fuel-air mixture ratio automatically while the pilot is otherwise engaged. Devices which fulfill these requirements are described in detail.

A resume of the tests with 100-octane (Army method) fuel by the Air Corps and the Wright Aeronautical Corp., clearly indicates the marked improvement not only in increased take-off power but also in the extremely low fuel consumption at cruising output made possible by the use of fuels of ultra-high octane rating.

THE aircraft-engine manufacturer, not unlike his more or less unfortunate co-workers in other activities of the automotive industry, is unhappily faced with problems of major magnitude if his product is to meet successfully not only current performance demands but also contemplated future requirements. In supplying the power-producing unit for a transportation field the byword of which is speed, and whose assaults on time and space have been so graphically illustrated by the shrinkage of maps, the aircraft-engine manufacturer has discovered often to his dismay that the time interval allotted by the industry for some such refinement as doubling the horsepower at twice the altitude is also subject to the same shrinkage process.

During the last ten years the air-cooled radial aircraft powerplant has undergone an intensive period of development which has placed it in a preeminent position in commercial as well as military service both here and abroad. The performance of present-day engines of this type fully justifies the faith and expectations of that small minority of designers who, some fifteen years or so ago, advocated the air-cooled radial engine in spite of the tremendous impetus and prestige gained by the water-cooled aircraft engine in the World War.

The design trend among various manufacturers of radial air-cooled engines during the last decade has found its ex-

[This paper was presented at the Annual Meeting of the Society, Detroit, Mich., Jan. 17, 1936, and at the Tractor and Industrial Power Equipment Meeting of the Society, Milwaukee, April 16, 1936.]

pression in the achievement of a notable decrease in pounds-per-horsepower ratio. This decrease is the result of increased piston displacement made possible by improved cooling of the combustion chamber and of higher crankshaft rotational speed brought about by the development of superior bearing materials as well as improved methods of lubrication. Increased power output for a given piston displacement has been attained as better fuels have made higher compression ratios and greater supercharging boosts possible. The reduction in frontal area and the advent of the ring cowl together with careful studies of airflow in the airplane installation have given a new grip on life to the air-cooled radial type of powerplant. Advances in the art of the metallurgy of steel and aluminum alloys have been reflected in greater reliability and increased life expectancy of all stressed parts of aircraft engines in general.

Graphically several of these trends may be shown in some degree by the data presented in Fig. 1. Plotted against the years 1925 to 1935 inclusive are representative values of piston displacement, rated crankshaft speed, brake mean effective pressure for sea-level rating, ratio of weight per brake horsepower at sea level, compression ratio, and average time between overhaul for a given type of air-cooled radial engine manufactured by the Wright Aeronautical Corp. during this interval.

Obviously such improvements in powerplant performance have resulted in better take-off and climb characteristics as well as higher cruising speed at greater altitude for the airplane itself. A greater degree of reliability and a gradual increase in the time interval between overhauls have also been contributory factors of no little importance in the establishment of the airplane as an everyday necessity in our civil and military life. With the fairly recent growth of air transportation as the most expeditious connecting link in a material way between remote islands and distant continents and the demand, therefore, to obtain not only financial economy of operation but also additional payload and safe cruising radius, has come a greater emphasis on the weight of fuel required for long-distance operations.

Likewise from the military standpoint, bombing flights require uniformity of fuel consumption from each airplane unit as well as a minimum fuel expenditure for the squadron; the extent of fighter and attack airplane operations depends on duration, granting of course the survival of the unit, upon fuel-tank capacity; and the maintenance of fuel supplies in time of war both on aircraft carriers and in air bases, possibly located in foreign territory, involves the handling and storage of immense quantities of fuel.

All such applications of the airplane, therefore, involve the extremely practical problem of the fuel consumption of its powerplant and what can be done about it. However, before we investigate the possibilities of doing something about fuel consumption, which it is agreed has become perhaps the major interest of the airline operators and the military services, it is desirable first to review briefly the factors which are inextricably bound up with the problems of efficiently converting the chemical energy in a given fuel into mechanical power within the combustion chamber of the air-cooled cylinder unit; although the air-cooled engine is mentioned in particular, the same considerations influence the fuel consumption of any internal-combustion engine.

Generally speaking it may quite safely be stated, I believe, that fuel consumption is a function of three basic factors: first, the specific design of the engine itself as a means for converting potential fuel energy into useful thrust by the propeller; second, the physical and chemical properties of the fuel itself together with its combustion characteristics while undergoing this reaction within the cylinder; and last, the modus operandi of introducing and regulating the fuel-air mixture supplied to the powerplant.

It seems to have been the common experience of most designers who have devoted both time and painstaking effort to the problem of high-duty air-cooled cylinder construction that high specific output per unit volume of piston displacement and low specific fuel consumption are attainable by careful attention to securing efficient cooling of the combustion chamber. While it was a somewhat common practice not so long ago to fuel-cool with fairly rich mixtures the air-cooled cylinder of high output, today we are interested in obtaining both fuel economy and efficient cooling of the cylinder unit by the application of fairly well-established principles of design often based on a rather painful accumulation of experience.

Considering the fact that within the combustion chamber of a modern type of air-cooled cylinder there is liberated a tremendous amount of heat energy per cycle of operation, it can be understood readily that prolonged service from the cylinder unit is possible only by the maintenance of operating temperatures below a critical value for the material which forms the combustion chamber. The amount of heat energy released is proportional to the weight of the fuel-air charge per cycle, and the present trend for increasing the charge weight through supercharging boost has, of course, greatly aggravated the cooling problem.

One of the most vigorous causes of overheating is detona-

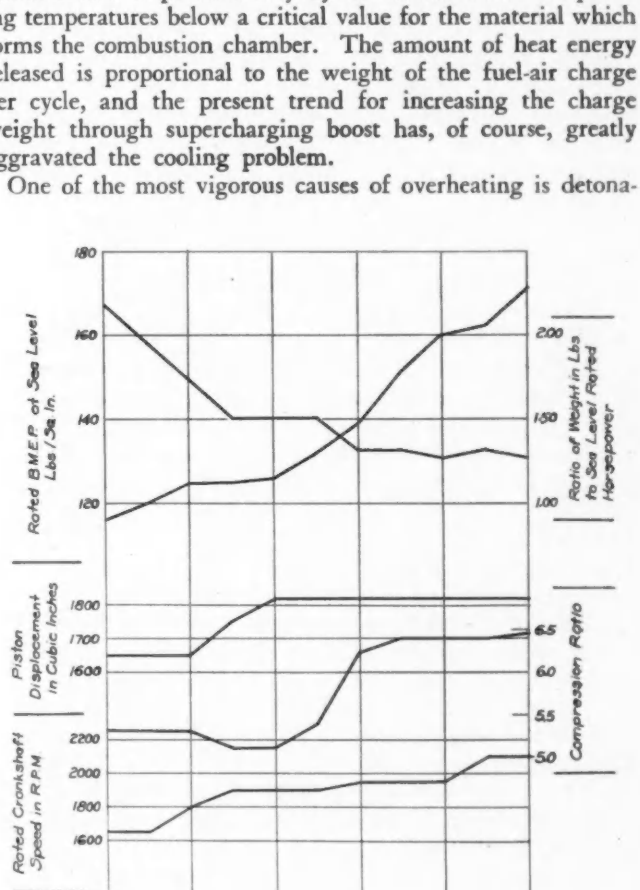


Fig. 1—Cyclone Engine Trends Over a Ten-Year Period

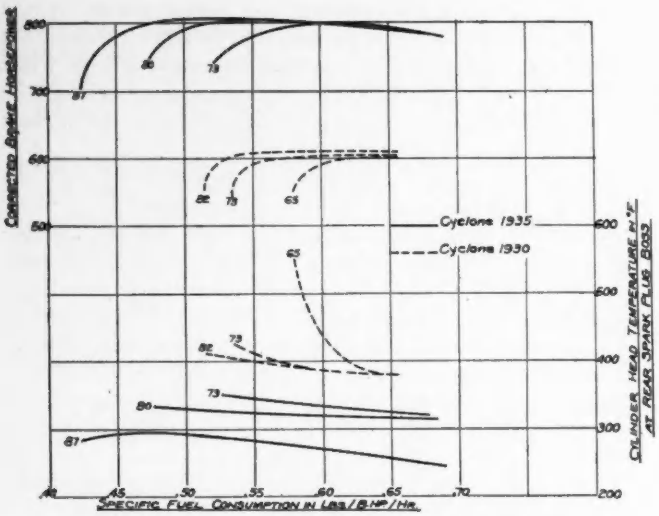


Fig. 2—Variation of Power and Cylinder-Head Temperature with Fuel Consumption and Octane Ratings (C.F.R. Method)

tion. The nature of this phenomenon has long been studied with results which are quite beyond the scope of this paper. It has been rather definitely established, however, among other findings, that the elimination of hot-spots within the combustion chamber is a major objective in controlling to a certain point the destructive habits of this unwelcome disturbance. In other words, it is most essential to maintain below the critical temperature that seems to induce detonation such necessary, but unsympathetic components of the combustion chamber as exhaust valves, spark-plugs, and pistons. Furthermore, the configuration of the combustion chamber itself should be such as to provide no nooks and crannies to foster localized areas of high temperature and to prevent a certain degree of turbulence essential to the proper rate of combustion.

Roughly speaking, heat energy to the extent of 65 per cent of the brake-horsepower equivalent delivered by the cylinder unit must be dissipated successfully from the combustion chamber. Some of this heat escapes through the piston to the cylinder walls and lubricating oil whence it is eventually dissipated by the cooling air. The walls of the combustion chamber including the cylinder barrel, valves and guides, spark-plugs, and exhaust-port surfaces must accommodate and transmit the balance of the heat energy, other than that in the exhaust gas itself, to the slipstream for ultimate disposal.

The problem of adequately cooling the combustion-chamber walls thereupon resolves itself into a matter of providing sufficient surface in intimate contact with cooling air of requisite volume and velocity to maintain the temperature of the interior of the combustion-chamber walls within definite temperature limits, plus wall sections of sufficient thickness to assure both proper conduction of heat energy and physical strength at the temperature limits established, and to withstand successfully mechanical stresses imposed by gas pressure, expansion, and vibration.

The use of fins on the exterior surface of the cylinder-head and barrel has become universal practice for obtaining the necessary surface on the air-cooled cylinder unit to maintain the temperature of these parts within operating limits. From a secondary standpoint, but nevertheless of no little importance, the finned type of construction also provides a high order of resistance to deflection under explosion loading on both head and barrel. To be effective the cooling fins should be as deep, thin, and as closely spaced as manufacturing practice and considerations of airflow will permit; especially when applied to those portions of the cylinder-head, such as the exhaust port, the area adjacent to the exhaust-valve seat and the spark-plug bosses, which receive the most heat.

Exhaust-valve materials have undergone a great improvement within the last decade, and steels have become available which not only possess a remarkable tensile strength at elevated temperatures but also are very resistant to scaling and corrosion. The use of ethylized fuels, however, has considerably narrowed the selection of exhaust-valve materials that are capable of withstanding the corrosive effect of this detonation inhibitor as it undergoes chemical reaction in the combustion process.

While some of these steels are capable of continuous operation at a bright-red heat, it has been found most desirable to lower the temperature of the exhaust valve as much as possible and thus improve the general cooling of the combustion chamber. A red-hot exhaust valve is not only an active agent in inducing detonation, but it also serves effectively to heat the incoming charge and to render spark-plug cooling difficult. The present-day operation of the exhaust valve at a greatly reduced temperature (best described, perhaps, as that which in full-throttle operation emits a faint red glow in complete darkness instead of the former bright cherry red) is attributable to the use of internal cooling of the head and stem. The pioneering efforts of S. D. Heron in sponsoring the salt-, and later, the sodium-filled exhaust valve are too well known to warrant any discussion at this point save to acknowledge his outstanding contribution to the art.

In considering the remaining units that exercise their respective functions in the combustion chamber and influence thereby the fuel consumption of the cylinder unit, there are the spark-plugs and the piston itself.

The requirements of the spark-plug may be stated generally as quite simple in definition but exceedingly difficult in practical attainment. That portion of the plug within the combustion chamber must operate at sufficiently low temperature, despite the adjacency of the exhaust valve, to prevent localized heating of the electrodes with consequent pre-ignition of the charge. On the other hand, the electrodes and exposed insulator must be maintained at sufficiently high temperature during the idling periods of the engine so that liquid fuel and lubricating oil will not accumulate and short-circuit the electrodes. The electrodes must be highly resistant to burning and should be capable of a high rate of heat dissipation to the spark-plug insert and cooler portions of the plug.

The insulating medium, of course, must have high dielectric strength, must withstand extremely high temperatures, and must resist lead fouling. As to the exterior portions of the spark-plug, it must be adaptable readily to radio shielding and must be capable of a rate of heat dissipation to the cylinder-head or cooling air sufficient to prevent burning of the ignition cable through heat conduction along the spindle. From a maintenance standpoint; ruggedness; ease of dismantling, cleaning, and adjustment of gap; as well as, of course, long service life are most essential. Obviously each type of engine, depending on compression-ratio, supercharging boost, fuel, and type of service, requires some sort of compromise in the above qualifications of the spark-plug in order to meet the operating conditions satisfactorily.

The piston is a potential source of much grief in that it is rather sensitive to temperature conditions, not to mention clearances, ring arrangement, and so on. Serving in the use-

ful capacity of heat dispenser, compressor, and the means whereby explosion pressure is converted through the piston-pin and connecting-rod into turning effort on the crankshaft, this rather elementary unit has an annoying habit of failing at just about the time it has established itself in the confidence of the designer. Such difficulties, where attributable to overheating and sticking of the rings, usually manifest themselves by scuffing of the skirt in the primary stage, followed by erosion of the lands and partial decomposition of the outer periphery of the head itself in the secondary stage. If inadvertently prolonged to the tertiary stage, the disease usually results in a catastrophe the diagnosis of which is most simply described as a washout of the powerplant, particularly in the radial type where all violence of this nature occurs in one rotational plane.

There are, of course, other types of failure, such as cracks in the head, skirt, or bosses resulting from extreme gas pressure or inertia loading, even in this enlightened age of "Y" alloy in the forged condition. Considering the piston as a component part of the combustion chamber with a large surface in intimate contact with extremely hot gases and by necessity forced to carry on without benefit of a direct cooling medium other than the incoming charge sweeping the top surface of the head and the lubricating oil splashing against the underside of the head, one can be a little more charitably inclined toward the shortcomings of this particular unit. In absorbing possibly 4 per cent of the total heat of combustion which must be dissipated from the combustion chamber, the piston must rely on its conductive properties to transmit this thermal energy to the cylinder walls and lubricating oil as quickly as possible. Hence the almost universal use of the aluminum alloys as piston materials for engines of high output. In addition to its superior thermal-conductivity characteristics, it is of course well known that aluminum, when used as a piston material, by its low specific gravity reduces very markedly the bearing inertia loading at high speed. The hottest portion of the piston head is naturally in the central portion probably somewhat displaced toward the exhaust valve. To prevent localized burning of the piston crown the flow of heat must occur readily through the head for dissipation to the lubricating oil, and radially to the periphery of the head for ready conduction through lands and piston rings to the cylinder walls. Adequate sections of material both in the head and behind the lands and grooves are most essential for proper heat flow and consequent cooling of the piston head.

Aside from its influence on fuel consumption through effective cooling of the combustion chamber, the piston is also involved in improved fuel economy obtainable through increased thermal efficiency as a result of higher compression ratios. By increasing the expansion ratio, and thereby the thermal efficiency, an increase in power output is accomplished with the same overall consumption of fuel, provided that the quality of the fuel is such as to prevent detonation and loss of power. Lower specific fuel consumption will, under these conditions, be obtained and lower combustion-chamber temperatures will result from the appreciable reduction in waste heat as more of the total heat energy in the charge is converted into useful work. Thus it is to be expected that cooler pistons, greater freedom from ring-sticking, and lower specific fuel consumptions will result from increased compression ratios as better fuels make such higher ratios possible.

Having surveyed after a fashion the manner in which low fuel consumption and the adequate cooling of the combustion chamber as a unit are associated, we have another item or two of engine design to consider in its relation to fuel economy before we refer to the characteristics of the fuel itself. Supplying the combustion chamber with a uniform combustible mixture of fuel and air suitably atomized and at the proper temperature is a distribution problem worthy of careful study and consideration. Fortunately the application of the so-called rotary-induction system to radial engines of high-power output, wherein the carburetor is located on the suction side of a centrifugal-type supercharger, contributed much to the even distribution of the fuel-air mixture to each cylinder. In passing through the supercharger the temperature of the mixture is increased due to the heat of compression, such temperature rise depending upon the tip speed of the impeller and the diffuser design.

Fuel characteristics and the performance of aircraft engines have always been closely inter-related. The air-cooled type of powerplant, especially in the early stages of its development, was very sensitive to the quality of fuel. No little credit for the continual improvement in its performance both as to higher brake mean effective pressure and lower specific fuel consumption is due to advances in the production and availability of better fuels.

In the first few years following the War there were two grades of fuel generally refined for use in military aircraft engines and known as Domestic Aviation Grade gasoline (D.A.G.) and Fighting Grade Aviation gasoline. The naturally aspirated engines of this period ran well on these fuels and low specific fuel consumption was not generally required.

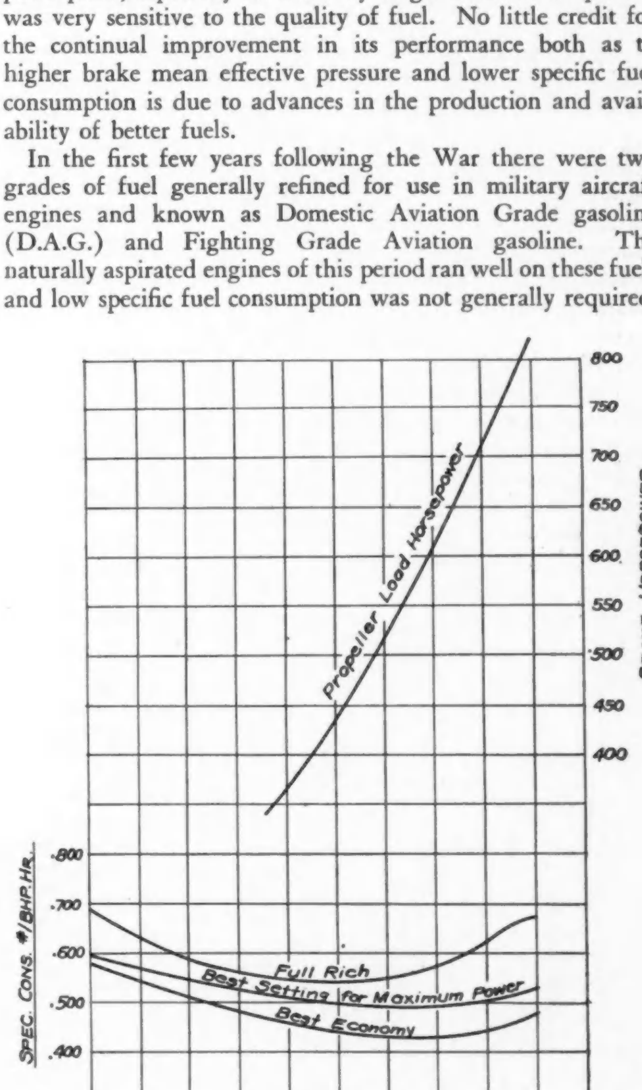


Fig. 3—Characteristic Full-Rich Specific Fuel Consumption Curve of Cyclone Engine on Propeller Load—Also Shows Specific Fuel Consumption Obtainable by Use of the Mixture Control

The occasional demand for a powerplant of high performance (135 lb. per sq. in. b.m.e.p. or better) utilizing high compression ratio pistons (6:1) at that time required the blending of the existing gasoline with up to 40 per cent of benzol for satisfactory operation. The increasing possibilities of the supercharged engine in military service some ten years ago led to intensive studies of fuel requirements for future procurement. The introduction of lead tetraethyl as a detonation inhibitor obsoleted the use of benzol which, as the chief aromatic blending agent, suffered a handicap because of its high freezing point and depreciation in knock rating under elevated-temperature conditions. On the other hand, the use of lead tetraethyl brought new problems, which stimulated the metallurgical industry in its efforts to produce a valve steel immune to ethyl corrosion.

The improvement of gasoline fuels in the last decade due to the pioneering efforts of the Bureau of Standards, the Cooperative Fuel Research Committee, the American Society for Testing Materials, the Air Corps Laboratory at Wright Field, the various refining interests and manufacturing companies is, of course, well known to everyone interested in this subject. The technique of knock rating based on the detonating characteristics of a mixture of iso-octane and normal heptane in a specified test engine was standardized sufficiently throughout the fuel industry so that aircraft-engine fuel specifications were written to include the octane rating as an index of the antiknock quality. For 1930 the Air Corps had standardized on 80-octane (C.F.R. method) fuel, and the following year the antiknock requirement was raised to 87 octane (C.F.R. method) through the increased availability and wider distribution of these high knock-rating fuels as a result of Air Corps standardization, and the various commercial aviation enterprises were able to take advantage of the increased engine performance resulting therefrom. Thus higher power output and lower specific fuel consumption became a practical possibility with an increased knock rating of the fuel.

Graphically this possibility for the Cyclone engine may be

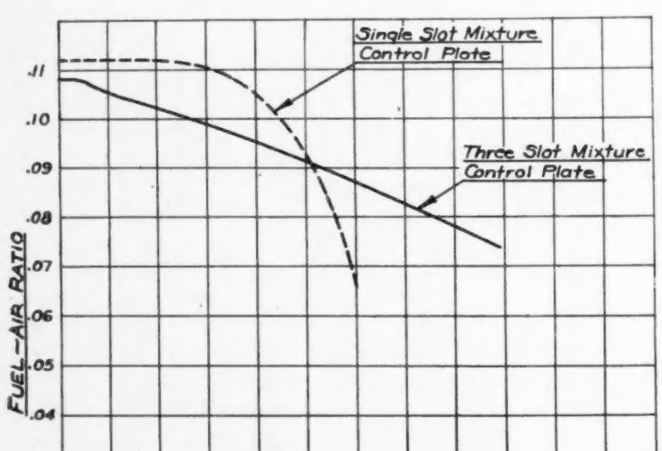


Fig. 4—Characteristic Effect on Fuel-Air Ratio of Control-Lever Travel with Single-Slot and Three-Slot Types of Mixture Control

illustrated by reference to Fig. 2. Here we have plotted the variation of horsepower and cylinder-head temperature against specific fuel consumption for three octane ratings of fuel based on the C.F.R. method. In dotted outline are shown characteristic curves for the Cyclone engine of 1930 operating on fuels of 65-, 73-, and 82-octane rating as described by P. B. Taylor in his Annual Meeting paper five years ago. The solid lines indicate the same characteristics of the present Cyclone engine operating on 73-, 80-, and 87-octane fuel. The marked improvement in power output, fuel economy, and cylinder-head temperatures for equivalent octane ratings is due primarily to the increased cooling efficiency of the current design of cylinder unit. The availability of 87-octane fuel also permits operation at appreciably lower specific fuel consumption at a noticeable reduction in cylinder-head temperature.

Since 87-octane fuel has been generally available for at least four years and since the possibilities of even higher engine performance with respect to power output and fuel economy through increased octane rating have been universally recognized, the obvious question arises as to why such a desirable improvement in the antiknock quality of aircraft-engine fuels has not been made since 1931. The answer involves technicalities of fuel-refining practice quite beyond the boundaries of this discussion. The problem is more intricate than it may appear and apparently is concerned, among other difficulties, with limitations on the susceptibility as well as knock rating of the existing clear gasolines available in quantity for aviation use, and on the concentration of lead tetraethyl per gallon of fuel dictated both by considerations of physical safety and the reactionary effect on the powerplant of its products of combustion. Nevertheless our fuel industry has continued steadily its efforts to produce better fuels with results to be described somewhat later in this paper.

In addition to the factors of engine design and the fuel characteristics that have a direct bearing upon the realization of fuel economy, there is also the matter of not only producing a combustible mixture and introducing it within the induction system, but also of controlling the ratio of fuel and air forming this mixture within the well-defined limits necessary to efficient combustion.

The most practical solution to this problem to date has involved the use of the carburetor which, although by no means the perfect instrument for the purpose, nevertheless, has a most impressive background of developmental experience and successful application to all kinds of internal-combustion engines since the very inception of this type of powerplant.

While it is not the purpose of this paper to dwell at length and in detail upon the theory and problems of carburetion, it will perhaps be of some interest to treat lightly of those phases of carburetion that seem to be doing well and to emphasize certain, shall we say, shortcomings of the carburetor which, until quite recently, have had an adverse effect upon the practical attainment of fuel economy in the operation of an aircraft engine. The carburetor has at best a most difficult assignment to fulfill when, in co-partnership with the aircraft engine, it may sway the balance either toward safety or disaster. It must function properly over a wide range of physical conditions to which the powerplant is normally subjected and provide within its own mechanism adequate compensation and adjustment for these variables. In supplying to the induction system an intimate mixture of fuel (preferably finely divided) and a reasonably correct propor-

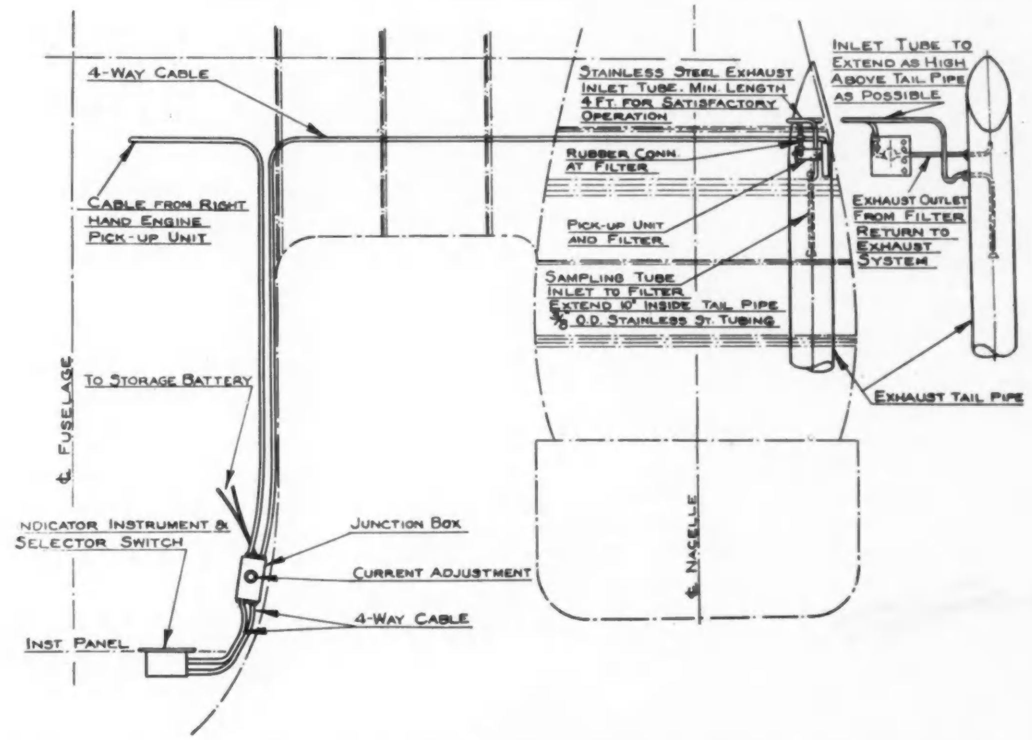


Fig. 5—Typical Installation of Cambridge Mixture Indicator in Twin-Engine Airplane

tion of air, the carburetor must adapt itself to all the requirements of the powerplant.

At idling speeds the mixture must be sufficiently rich to compensate for the residual exhaust gases within the cylinder and intake pipe and to promote smooth operation at low speeds. When "given the gun" the engine must accelerate smoothly and without backfire from closed throttle to the take-off or emergency position of the throttle within approximately 0.6 sec. To provide a temporary enrichment of the mixture during this acceleration procedure in compensation for inadequate suction at the main jets and lack of proper vaporization of fuel resulting from momentary low velocity of air through the venturi, the correct volume of fuel as an accelerating charge must be injected into the induction air stream as the throttle is suddenly moved to the open position. During periods of operation at high output, such as take-off or emergency, it is desirable as a precautionary measure both from the standpoint of improved acceleration and optimum cooling of the combustion chamber, to enrich the mixture by permitting an increase in fuel flow to the main discharge nozzles through the so-called economizer system.

The other function of the economizer system is to permit, through closing of the economizer valve interconnected with the throttle, a reduction in fuel flow to the main discharge nozzles throughout the cruising range of the engine speed as the throttle is retracted from the open position. Further economy in fuel consumption as well as compensation for enrichment due to decreased air density at altitude may be obtained by the use of the mixture-control mechanism. As a final prerequisite for satisfactory application to an aircraft engine, the carburetor must continue to function properly regardless of the attitude in which it may find itself due to the maneuvering of the airplane. Susceptible and sensitive to throttle opening, engine speed, atmospheric density and temperature, fuel viscosity and pressure, the carburetor nevertheless has given a good account of itself because, or possibly in spite of, the engine manufacturer, airline operator, and pilot.

There is, however, the matter of improvement in the practical attainment of fuel economy. In investigating this phase of carburetion let us first refer to Fig. 3 showing characteristic fuel-consumption curves on propeller load obtainable, for example, with a Cyclone engine and Stromberg carburetor. For the purposes of this discussion we are primarily interested in the engine-speed range of 1600 r.p.m. to 2100 r.p.m., which covers the service-operating conditions throughout the life of the powerplant. It will be noted that between 1900 r.p.m. and 2100 r.p.m. the specific fuel consumption full rich increases from 0.57 to 0.67 lb. per b.hp-hr. as the fuel flow is augmented by the economizer system previously described. Thus, for take-off and emergency operation, the fuel consumption is considerably increased. Since, however, these periods of high-power output constitute an extremely small proportion of operating time (possibly 1 per cent or less of the life of the powerplant), the fuel consumption during this stage of service is of little import. Therefore, between 1650 r.p.m. and 1950 r.p.m. is the principal range of service to be considered for improving the economy in fuel consumption. As explained previously some reduction in specific fuel consumption in the cruising range is made possible by the economizer system which provides the enriching hook evident in the full-rich consumption curve in Fig. 3 with the increase in engine revolutions toward rated speed. Further economy in specific fuel consumption is possible by bringing the mixture-control system into play.

Restricting the fuel flow through the main discharge nozzles of the carburetor to compensate for decreased density of the air or to lower the fuel-air ratio for improved economy may be accomplished in several ways. The discussion in this paper will be confined to the back-suction type of mixture control, which type has been found extremely satisfactory in the

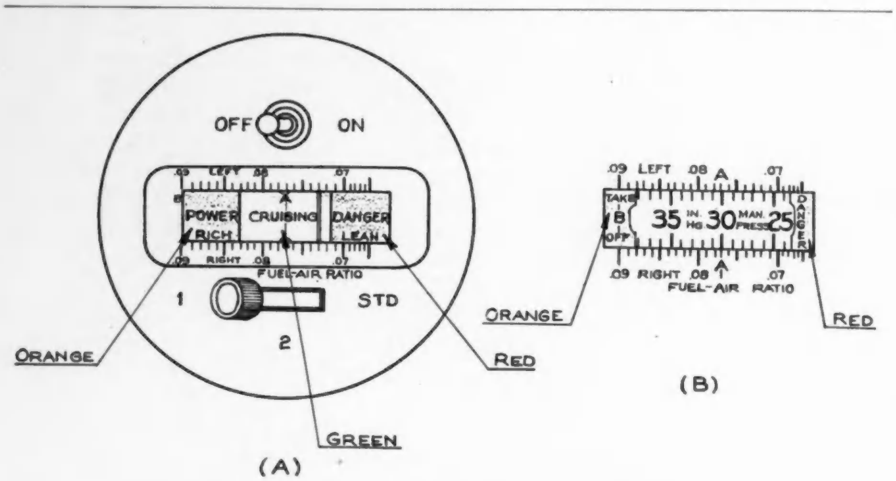


Fig. 6-*A*—Cambridge Mixture Indicator
***B*—Proposed Scale Based on Manifold Pressure**

larger models of Stromberg carburetor. The principle of operation is essentially a controlled suction upon the fuel in the float chamber which, therefore, is in opposition to the suction of the main discharge nozzles in the venturi. The source of the suction imposed on the float chamber is likewise obtained from the venturi air passage and is controlled in degree by means of a slotted-disc valve, opening as necessary to both atmosphere and the float chamber.

In considering the effect of specific fuel consumption on the power output of the engine it has become common practice to establish three ranges of carburetor performance generally defined in this country as "full rich", "best setting for maximum power" and "best economy". Full rich may be defined as the position of the mixture-control lever giving maximum fuel flow through the carburetor. Best setting for maximum power is that adjustment of the mixture-control lever which results in the development of maximum power output with minimum fuel flow. Best economy may be described as that position of the mixture-control lever giving a minimum specific fuel consumption which is consistent with the safe and continuous service operation of the powerplant for the output required.

Evaluated in terms of specific fuel consumption the results of these variations are illustrated in Fig. 3. Since aircraft carburetors have long been equipped with a mixture-control system for obtaining low fuel consumption, the question naturally arises why the engine operator has not been able satisfactorily to avail himself of the improvements in combustion-chamber design, of more efficient engine-installation cooling, and of superior fuels which make real fuel economy practicable. The answer is involved in several important factors bearing on the fundamental nature of flight operation itself:

(*A*) Taking into account first the human element, let us consider the natural reactions of the average pilot who may or may not be the lone occupant of the cockpit. During take-off or in any emergency maneuvering near the ground in which high-power output and almost instantaneous acceleration without fail are most vital to his own safety as well as to that of his passengers, the pilot will of necessity keep the mixture control in the full-rich position. So essential is his attention to the rapidly changing state of affairs outside the cockpit that he can devote scarcely a glance to his instruments. Having gained some altitude and having overcome successfully the obstacles incident to the take-off and to his proximity to the ground, he throttles (assuming, of course, that the average pilot is also the ideal pilot) the engine somewhat, depending in degree upon his load and desired rate of climb, and perhaps takes a look at the instruments. The engine is still running smoothly (we hope) and so he continues his climb with the mixture control in the full-rich position. He has heard and rightly so that cylinders may burn and pistons stick if that mixture-control lever is moved around rather indiscriminately, especially when the manifold-pressure gage still registers boost. So he is content to leave well enough alone. Upon arriving at his cruising alti-

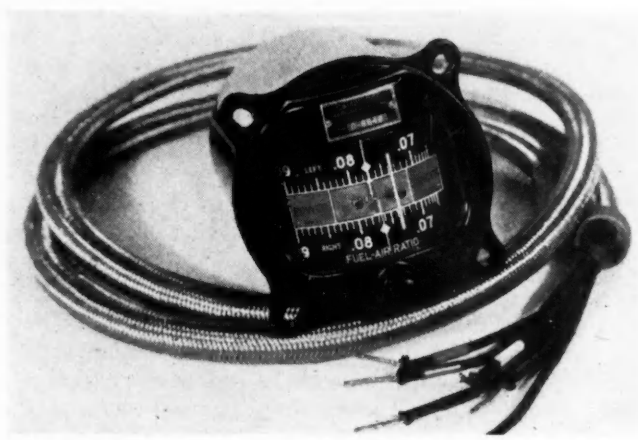


Fig. 7—Cambridge Mixture Indicator for Twin-Engine Installation

tude, he further reduces the throttle opening to give the revolutions per minute and manifold pressure prescribed by his power-control charts if available, or otherwise according to his experience and judgment. He then decides something must also be done about the fuel consumption. So, watching the tachometer and perhaps the thermocouple instrument, he slowly pulls the mixture-control lever until the tachometer needle begins to flutter. He has probably read an instruction issued by the engine manufacturer in a handbook that best economy may be obtained for cruising by leaning out the mixture until the tachometer needle drops approximately 20 r.p.m., then enriching the mixture slightly to regain the lost revolutions; all of which is rather indefinite and a matter of experience and judgment. The average pilot, reading in the service bulletins of the engine manufacturer that it is necessary to exercise every precaution in the use of the mixture control, much prefers to let nature take its course and therefore allows the engine to operate with a mixture decidedly on the rich side.

In the case of a modern transport the co-pilot usually handles the controls under cruising operation while the pilot busies himself with his charts, slide rule, and flight log, checking against his preliminary flight plan and instructing the co-pilot as necessary. From the time of switching "on" a

main fuel tank which is noted on the flight log until the time of switching "off" (also entered in the log) when the tank has been drained, it is possible to determine with fair accuracy the hourly rate of fuel consumption under existing conditions of flight. This method has significance insofar as specific fuel consumption or fuel economy at a certain cruising output of the powerplants is concerned, only if the manifold pressure and revolutions per minute have been maintained constant during the time interval in question. No indication is given therefrom as to whether the mixture control has been adjusted uniformly for each powerplant to obtain approximately equal fuel economy from each engine.

This regulation of the fuel-air ratio is undoubtedly becoming a more and more difficult procedure as powerplants, propellers, the variety of cockpit instruments, and the technique of flight operation become increasingly more complex. There is so much to engage the concentration of our average pilot that the matter of fuel-mixture adjustment must of necessity often be deferred until the more urgent complications are well in hand. Then later, while economically minded and reaching for the mixture-control lever, he again recalls having heard, and rightly so, that burned exhaust valves and seats, excessive wear of cylinder barrels, pistons, and rings, as well as valve guides, result from cruising on excessively lean mixtures. So, having until quite recently no qualitative indication of what his movement of the mixture-control lever was accomplishing other than the readings of the tachometer and thermocouple cylinder-head temperature, the average pilot again prefers to play safe and set the mixture on the decidedly rich side. And he probably also pushes it to the full-rich position shortly after beginning his descent, lest this procedure be overlooked preparatory to landing.

In assuming such practice no adverse criticism of the pilot is intended as the responsibilities of his job certainly warrant those considerations of safety in which the end justifies the means. And possibly in the case of the co-pilot system there may be some degree of injustice in the preceding description, but it is quite safe to assume that so long as the pilot has no visual assurance that the mixture strength is being regulated within the prescribed and safe limits, he will purposely and justifiably keep to the richer value of the fuel-air ratio.

(*B*) Another recent development also has complicated the adjustment of the mixture strength to economical proportions. This development is the increasing use of the constant-speed propeller. When operating with this equipment the pilot is no longer able to adjust his mixture control by observing the effect on engine speed since this value remains constant regardless of variations in power with mixture strength.

(*C*) The functioning of the mixture-control system has been by no means perfect insofar as regularity of control determined by degree of lever travel is concerned. The original design of back-suction mixture control on the Stromberg carburetor embraced a slotted-disc valve of special contour for the purpose of reducing the sensitivity of adjustment. In Fig. 4 is illustrated the characteristic action of this single-slot control. It will be noted that, for a considerable degree of movement of the mixture-control lever, relatively little change in the fuel-air ratio was accomplished. At a certain point, however, the leaning effect begins and increases very rapidly with the movement of the lever.

Within the last year Stromberg has introduced the three-slot mixture control with greatly improved characteristics. Fig. 4 shows the effect of these changes wherein will be noted the more gradual reduction in fuel-air ratio with increasing travel of the mixture-control lever. This modification has been a decided advantage in adjusting the mixture strength in flight. However, until the pilot is entirely relieved of the responsibility of mixture-strength adjustments, as of necessity he must be in certain types of military fighting equipment, and until by a glance at an instrument he can receive assurance that his engine is operating on a fuel-air ratio that is within safe limits, the successful realization of the fuel economy inherent in the modern design of the air-cooled radial powerplant will not be attained in flight service.

(*D*) We have noted in Fig. 3 that, as the output of the engine is increased in terms of higher revolutions per minute beyond the recommended cruising range, it has been found expedient to provide the powerplant with a somewhat richer mixture. Since the horsepower on propeller load increases as

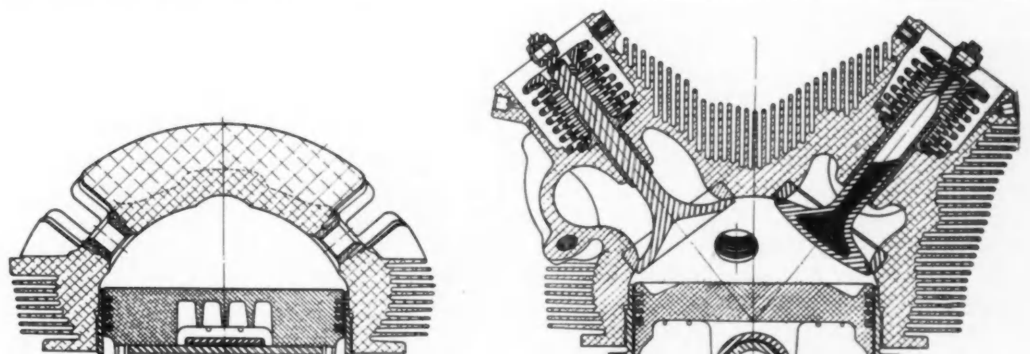


Fig. 8—Constructional Features of Modern Cyclone Cylinder-Unit Assembly with Piston

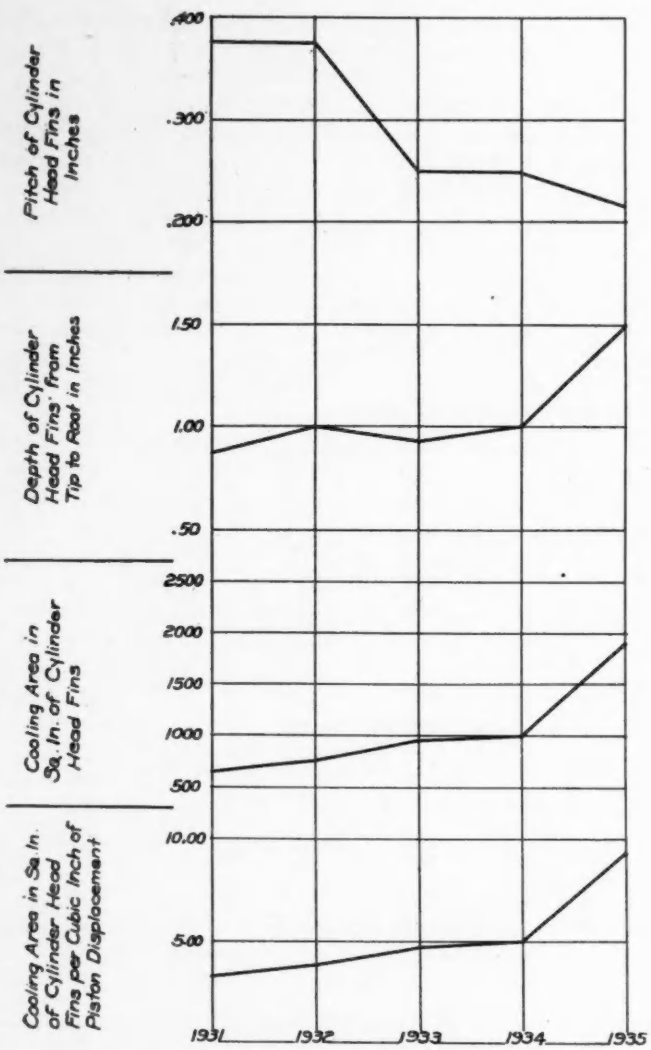


Fig. 9—Cyclone Cylinder-Head Cooling Factors Over Five-Year Period

the third power of the engine speed, it is evident that any appreciable increase in propeller speed and resultant thrust necessary to maintain a given schedule against headwinds or other delaying influences will take its toll in higher overall fuel consumption. Likewise, it follows that the speeding up of schedules due to competition or for other reasons may be done at the expense of fuel consumption, especially if the airplane performance is on the ragged edge and its prevailing cruising speed already demands a power output in the upper range of the recommended cruising-power bracket.

It is but natural that the many difficulties involved in obtaining a reliable and qualitative indication of the effects of variations in fuel-air ratio in flight as well as the increasing requirements for improved fuel economy in all flight operations should result in the demand first, for an instrument—compact, rugged, relatively simple in installation, and reliable—which would measure accurately the results of changes in the fuel-air ratio; second, the development of an automatic mixture control which at will would relieve the pilot of the necessity of manually controlling the fuel-air ratio for efficient operation of the powerplant under changing conditions of altitude, manifold pressure, temperature, and revolutions per minute incident to flight whether climbing, cruising, or descending in fair weather or foul.

Recognizing then this urgent need for some sort of device which would provide the pilot with visual evidence of the effect on the powerplant produced by a change in the fuel-air ratio other than an indication on a thermocouple instrument and possibly the tachometer, the Wright Aeronautical Corp. somewhat over a year ago made a survey of the commercial exhaust-gas analyzers available on the market. An exhaust-analyzing unit developed by the Cambridge Instrument Co. for the use of automotive service stations in making carburetor adjustments seemed promising, so the makers of this device were encouraged to adapt it to aeronautic use.

When redesigned by the Cambridge Instrument Co. for installation in the airplane, the Cambridge mixture indicator as an assembly consists fundamentally of a gas-analyzing cell, a junction box, the indicator instrument, and the necessary tubing and wires. A typical installation is diagrammatically illustrated in Fig. 5 for the left-hand engine of a modern transport. The gas-analyzing cell is mounted in the engine nacelle conveniently adjacent to the exhaust tail-pipe. Through a stainless-steel inlet tube, with minimum length of 4 ft. and so connected to the tail-pipe as to extend for a distance of 10 in. toward the exhaust collector ring, a sample of the exhaust gas is conveyed to the analyzing cell.

This analyzing cell consists of a filter packed with bronze wool through which the sample of exhaust gas passes, and a brass block suitably chambered to receive coils of extremely fine platinum wire so connected as to form the well-known Wheatstone bridge. Two branches of the bridge are sealed in chambers which, through a labyrinth passage, are in communication with the sample of exhaust gas which diffuses from the filter. The other two branches of the bridge, identical in all respects, are located in passages which are in contact with a standard atmosphere consisting of air saturated with vapor from a replenishable supply of water. After passing through the analyzing-cell filter, the exhaust gas preferably is returned to the tail-pipe through an outlet tube also made of stainless steel.

The basic principle underlying the operation of the Cambridge mixture indicator is that of an unbalanced Wheatstone bridge deflecting a sensitive galvanometer in proportion to a change in resistance of the two branches of the bridge which are immersed in the exhaust-gas atmosphere. The resistance of these two branches of the bridge in contact with the exhaust gas is a function of the thermal conductivity of the variable constituents of the exhaust gas. As the thermal conductivity of the exhaust gas changes with varying proportions of carbon dioxide, carbon monoxide, oxygen, hydrogen, and nitrogen resulting from adjustment to the fuel-air ratio, the platinum coils vary in temperature and, consequently, in electrical resistance. Thus an unbalanced bridge circuit is established since the other two branches in contact with the standard atmosphere or saturated air at the same temperature as the exhaust gases, are unaffected. There is no change in the thermal conductivity of the saturated air, and hence there is no variation in the resistance of this branch of the bridge.

Current flowing from the 12-volt battery has already stabilized the temperature of the platinum coils at approximately 260 deg. fahr., and any unbalance due to changes in the thermal conductivity of the exhaust-gas atmosphere surrounding two branches of the bridge is registered by a deflection of the galvanometer. Such deflections of the indicating instrument are calibrated in terms of fuel-air ratio. The galvanometer or indicating instrument has been balanced at a fuel-air ratio indicated on the instrument dial by the line

marked *A* in Fig. 6. Consequently any decrease in carbon dioxide, which has a thermal conductivity approximately half that of air, and an increase of carbon monoxide and hydrogen from enrichment of the mixture swings the galvanometer pointer toward the high fuel-air ratio end of the calibrated scale. The analyzing cell is particularly sensitive to an increase in hydrogen since this gas has a thermal conductivity approximately six times that of air. This fact may be misleading in the indication of fuel-air ratios as will be pointed out later. The thermal conductivities of carbon monoxide, oxygen, and nitrogen are equivalent, for the purposes of the analyzer, to that of air so obviously the indicator is largely sensitive to changes in the relative amount of hydrogen, and, to a lesser extent, carbon dioxide in the exhaust gas.

In leaning the mixture within certain limits the carbon monoxide burns to carbon dioxide, the amount of free hydrogen decreases, and that of oxygen increases. The predominance of carbon dioxide in the exhaust gas and the minimum amount of hydrogen so influences the thermal conductivity of the sample atmosphere that the galvanometer deflection is toward the low end of the fuel-air ratio calibrated scale. This indication is obtained only when the mixture has not been leaned to the point of detonation. With the advent of this phenomenon, free hydrogen as well as free carbon are liberated within the combustion chamber and pass into the exhaust gas. This excess of hydrogen immediately deflects the pointer toward the rich direction of the scale which, while misleading until experience has been acquired with the functioning of the instrument, is nevertheless an excellent warning of detonation. A fluctuation of the instrument pointer likewise indicates incipient detonation.

Provision is made for three adjustments to maintain the accuracy of readings on the Cambridge mixture indicator. The pointer should stand at "mechanical zero", or at *A* when the switch is in the "off" position so that no current is passing through the instrument. If not, it may be brought to this position by turning a small adjustment screw above the scale. The current passing through the instrument must be maintained at a constant value so that no variations in the heating of the platinum coils occur from this source.

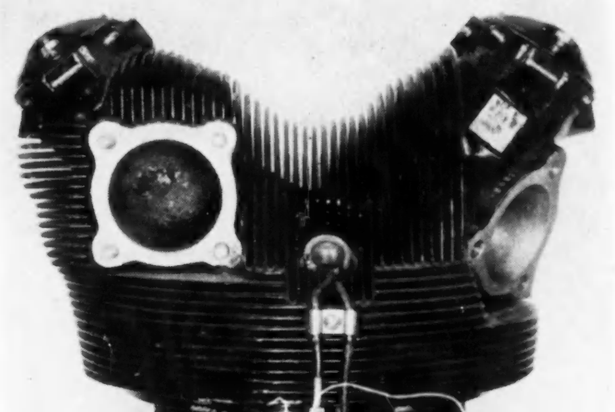


Fig. 10—Modern Cyclone Cylinder Unit

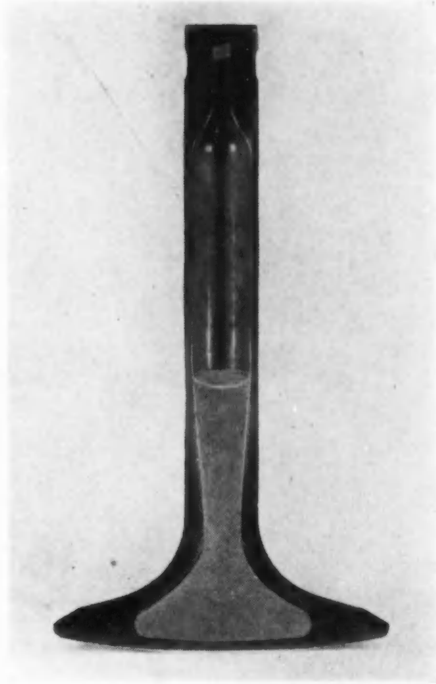


Fig. 11—Section of Cyclone Exhaust Valve Showing Hollow-Head Design Partly Filled with Sodium

This second or "current" adjustment is made by turning the selector switch on the bottom to the "standard" position with the current switch on top in the "on" position. Under these conditions the pointer should deflect to the extreme left side of the scale marked *B*. If it does not move to the *B* position, the necessary adjustment may be made by turning the rheostat on the junction box.

The third or "electrical zero" adjustment should be made after the first two have been checked and is necessary only at intervals of three months to a year. This adjustment establishes the pointer at the line marked *A* when all the branches of the Wheatstone bridge are subjected to a standard atmosphere of air saturated with water. To make this adjustment the filter cover and the bronze wool are removed and a rag wet with water inserted within the filter compartment of the analyzing cell. No residual gas should remain within the cell. After sufficient time, at least half an hour, has elapsed to permit saturation of the air, the current is switched on. After half a minute or so the pointer should come to rest at *A*. Any necessary adjustment to bring it to this position may be made by turning the rheostat screw on the instrument. The bronze wool and the filter cover are, of course, replaced after this test. Occasionally it will be necessary to remove the accumulation of oil and carbon residue by washing the bronze wool in gasoline and then in water, and also to saturate the wick with water to provide the standard atmosphere for two branches of the Wheatstone bridge.

The indicator instrument itself is, of course, mounted in the cockpit and is provided with a switch for connection to the battery line. In the early type of instrument as illustrated in Fig. 6 an additional switch permits connecting the analyzer unit from either engine to the indicator at will. The instrument scale was not only calibrated numerically in fuel-air ratio but also provided with three colored bands in the

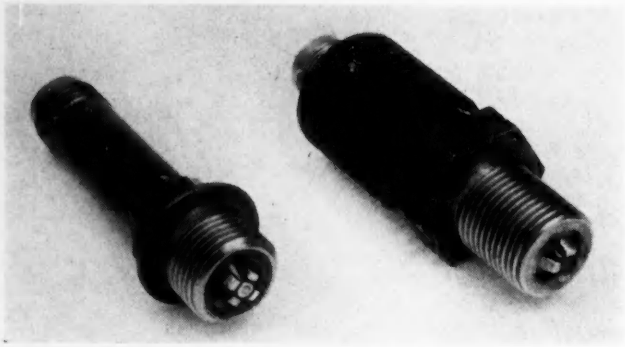


Fig. 12—Wright Finned Spark-Plug (shown on right) and Standard Radio-Shielded Spark-Plug (on left)

significant operating ranges: red for "danger" on the lean end of the scale, green for the economical "cruising" range, and orange for "power" operation on the rich end of the mixture ratio. For visibility at night the average desirable cruising mixture-ratio mark and the indicating needle are luminous.

A later type of instrument is shown in Fig. 7. This instrument is designed especially for twin-engine installations and combines two independent indicating units utilizing one instrument in the cockpit. Thus a constant check may be maintained, and equivalent fuel consumption obtained from each powerplant.

In the development of this instrument there have been some difficulties, of course, which have been concerned chiefly with incorrect installation. The condensate of the exhaust returned from the analyzing cell is corrosive by nature and, when discharged against an aluminum surface, results in ultimate deterioration of this material. This difficulty has been corrected, as noted in the installation drawing, by returning the exhaust discharge to the tail-pipe. Some unsatisfactory functioning of the mixture indicator has been occasioned by failure to locate the inlet sampling tube in a pressure area within the exhaust pipe due to bends, adjacent stacks, or turbulence. This condition may be remedied by checking the flow of exhaust gas into a bottle of water and then relocating the sampling tube as necessary to obtain a substantial flow of gas.

A further revision of the twin-engine indicator is now in progress which concerns the calibration of the instrument scale as indicated in Fig. 6. For the further guidance of the pilot a scale of absolute manifold pressure in inches of mercury has been added, supplementing the fuel-air ratio scales which remain intact. By correlating the reading of the manifold-pressure gage with the corresponding scale on the Cambridge mixture indicator, the pilot may so regulate the mixture-control levers as to arrive at the recommended mixture strength when the indicator pointers coincide with the value of the respective manifold pressures registered on each boost gage. During take-off at the full-rich setting of the mixture control the pointers will swing to the "take-off" position at the extreme left-hand edge of the scale. As the engines are throttled for the climb at a given manifold pressure, the pilot leans out the mixture of each engine until the indicator pointers arrive at the given manifold-pressure value on their respective scales.

With increasing altitude it will, of course, be necessary for maximum economy continually to adjust the mixture controls toward the lean end. For cruising at a given altitude, revolutions per minute, and manifold pressure this procedure becomes simplified in that continual readjustment of the mixture strength is unnecessary. However, should the indicator pointers begin to fluctuate rapidly as an indication of detonation or the thermocouple instrument register excessively high cylinder-head temperatures for one reason or another, the cautious pilot will enrich the mixtures to a manifold-pressure scale value higher than the actual engine manifold-pressure readings on his boost gages. Some adjustment of the scale probably will be desirable to accommodate one type of instrument to engines of different power ratings as determined by the supercharger gear-ratio and permissible boost.

In flight service the Cambridge mixture indicator is becoming a useful instrument in the realization of fuel economy. Despite the application of the automatic mixture control to relieve the pilot to a large extent of the mixture-control nuisance, the mixture indicator undoubtedly will be used as a valuable adjunct and supplementary instrument that visually assures the pilot that the automatic mixture control is functioning properly; the mixture indicator enables him to obtain additional fuel economy, should he so desire, beyond the automatic range of mixture-control operation; and it indicates a condition of incipient detonation in the engines.

The foregoing and somewhat general remarks on the factors affecting fuel consumption apply, of course, to any air-cooled type of powerplant. A specific reference to the possibilities of improving fuel economy from the standpoint of advanced engine design, of better regulation of the fuel-air ratio, and finally from the results obtainable with fuels of higher quality, naturally involves the presentation of data by the writer based on the activities of his own company if the details are to reflect the recent progress with which he is familiar, employed toward the solution of current problems.

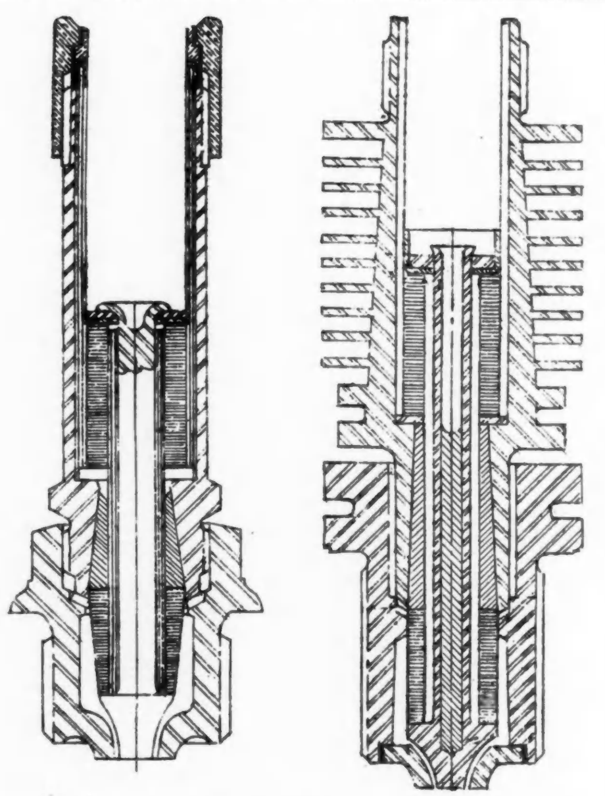


Fig. 13—Sectional Views of Wright Finned Spark-Plug (on right) and Standard Radio-Shielded Spark-Plug (on left)

Returning again to the matter of combustion-chamber design, let us refer to Fig. 8. Here we have two sectional views of the current Cyclone cylinder unit including the piston assembly. The cylinder-head of cast "Y"-alloy has a hemispherical combustion chamber which has been found to be universally satisfactory for engines of high-power output. This dome-shaped combustion chamber, of course, offers maximum resistance to deformation, is of minimum wall area, and is readily adaptable to efficient valve-porting. The sloping section of the dome also insures impingement of the cooling air stream against its outer surface and induces a scrubbing action which facilitates heat transfer.

In designing the finning arrangement of this cylinder-head, much effort was directed toward obtaining the maximum cooling area by utilizing extreme depth as well as close pitch of the cooling fins. Some of this effort is expended customarily on the pattern shop and foundry in convincing these departments that the design is practical and a feasible manufacturing set-up. Usually the patternmaker views any new cylinder-head drawing with a dubious and pessimistic eye and, after a sympathetic conference with the foundryman, the design is pronounced impracticable if not impossible. After a bit of persuasion, however, the problem is accepted as a personal challenge to the art of the patternmaker and foundryman and, within a surprisingly short period of time, sample castings are delivered to the engineering department for examination. Indeed, too much credit cannot be given these two departments for the improvements that have been made in cylinder-head production during the last few years.

That this development is no easy task is evident from a consideration of the data presented in Fig. 9. Here it will be noted in the upper curve that the fin pitch within the last five years on Cyclone cylinder-heads has decreased from 0.375 to 0.218 in. Likewise, as indicated in the next curve, the depth of the cylinder-head fins of the combustion chamber has increased from 0.875 in. in 1931 to 1.50 in. in the present head. The net result of this decrease and increase is shown graphically by the next lower curve wherein it will be noted that the cooling area of the Cyclone cylinder-head fins in this given time interval has been increased from 620 to 1900 sq. in. On the basis of square inches of cylinder-head fin area per cubic inch of piston displacement this increase in ratio is in the order of 3.2 to 9.4 To this predominantly essential factor of increasing combustion-chamber fin area per unit of piston displacement may be attributed, in a large degree, the improvement during the last five years in rated b.m.e.p. from 138 lb. per sq. in. to 172 lb. per sq. in., and the superior cooling efficiency of the present Cyclone cylinder-head under extremely adverse conditions.

In shape the cylinder-head fins taper slightly to facilitate withdrawal of the pattern from the mold. The fins of the steel cylinder barrel, however, have parallel sides which permit machining with multiple cutters that exert no side-thrust on the fins and complete a relatively large radius at the root of the fin. Air deflectors, or baffles, are used on both cylinder-head and barrel to guide the flow of cooling air tangentially where it will do the most good, namely to the hottest portions. Intelligent direction of the cooling air stream by means of baffles and the ring cowl has had an important bearing on the reduction of drag, a consideration which not so long ago was a most disturbing factor in an otherwise promising future for the radial air-cooled power-plant. The thin sections of the fins on both head and barrel as well as their rather close pitch and extreme depth have

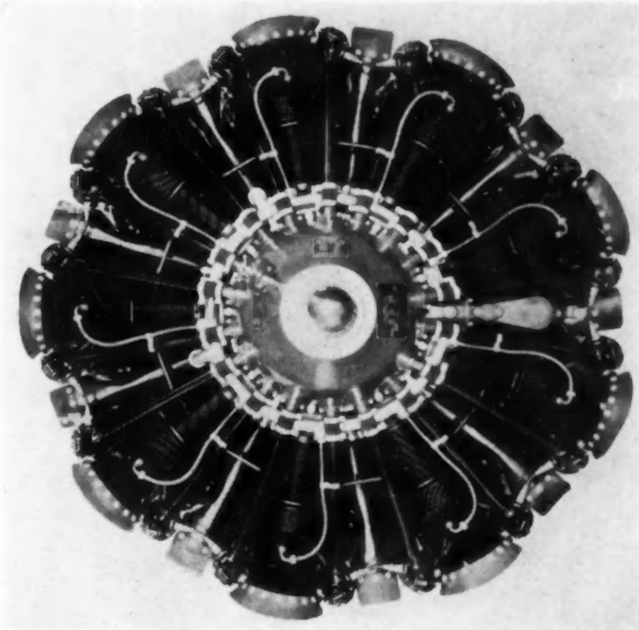


Fig. 14—Front View of Cyclone Engine

resulted in no increased manufacturing mortality either in fabrication or in handling. From the standpoint of airflow there is still sufficient turbulence between adjacent fins to promote effective scrubbing of the surfaces with no appreciable boundary layers of stagnant air. Having considered the cooling-area factors on the exterior of the combustion chamber, let us next refer to some of the interior details of the cylinder unit illustrated in Fig. 8 and Fig. 10.

The importance of a cool exhaust valve to prevent detonation has been previously stressed. In the Cyclone exhaust valve, developed over a period of many years in conjunction with the two leading manufacturers of aircraft-engine valves, a hollow-head design filled with sodium has proved most effective in eliminating this hot spot from the combustion chamber. The actual section of this valve is shown in Fig. 11. The cavity within the head is carefully machined and provided with large radii to prevent cracks due to stress concentration. The ample sodium capacity of the head effectively reduces the temperature of the central area within the combustion chamber, and through the hollow stem is provided, by means of mechanical agitation, a ready transfer of this heat energy to the valve guide and boss. The temperature of the peripheral area of the valve head is reduced by the escape of heat through the face of the valve into the insert and cylinder head.

Because, during 280 deg. of crankshaft travel, this face of the valve is scoured by exhaust gases at extremely high temperatures, it has been found desirable to apply by welding a very hard wearing surface of stellite to the austenitic nickel silicon chromium tungsten steel of the valve itself. Working against an insert of nickel silicon tungsten chromium steel the hard faces of the valve and insert are relatively immune to particles of carbon or scale which occasionally are entrapped on the sealing surface of the valve or insert and which, on softer materials, result in pitting and erosion of these faces. The hardened valve face and the steel insert are also an effective means of minimizing pounding-in of the insert face and wear of the seating surface of the valve itself due to the impact loading to which it is subjected. A nitrided

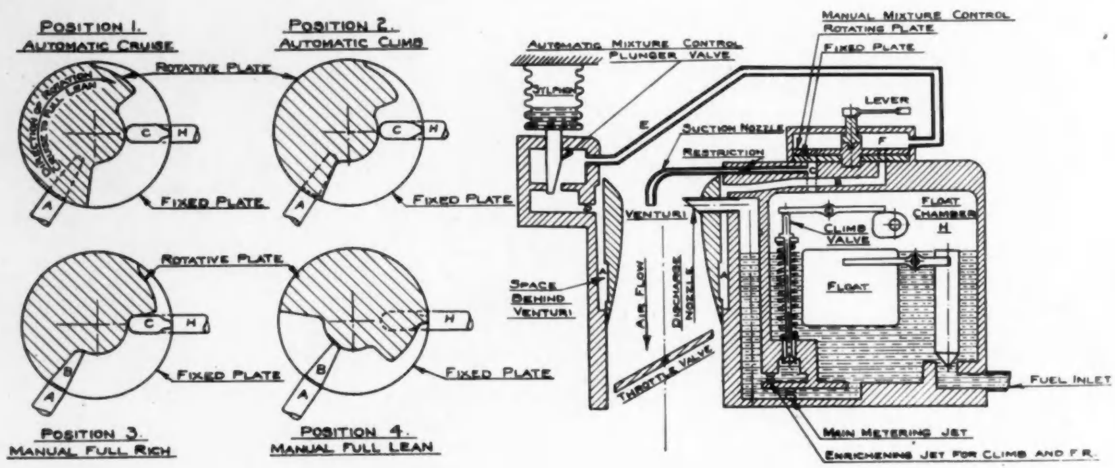


Fig. 15 — Diagrammatic Sketch of Automatic Mixture-Control System on Bendix-Stromberg NA-F7 Carburetor

stem and cobalt chrome tip offer extreme resistance to wear from the action of the rocker roller.

Compared to the exhaust valve the inlet valve, which is constantly cooled by the fuel-air mixture, leads a relatively carefree existence and is therefore subject to comparatively little trouble. The tulip shape illustrated in Fig. 8 has been found generally desirable for effective flow characteristics with minimum restriction through the inlet-valve port. In the matter of port design careful attention to the elimination of sharp corners on valve-guide bosses and valve-seat inserts induces an unrestricted flow of the induction mixture and provides ready egress for the exhaust gases. This overhead type of valve construction with the included angle of 75 deg. between valve axes provides the degree of turbulence necessary for efficient combustion and high power output per unit of piston displacement.

Effective location of the spark-plugs in the cylinder-head of the internal-combustion engine has been the object of much research, usually by the method of trial and error. In the hemispherical combustion chamber limitations of space, internally due to the unusually large diameters of valves and seat inserts and externally due to interferences with valve ports and rocker boxes together with the necessity for subjection to the cooling air stream, restrict considerably the choice of location. As noted in Fig. 8 the two spark-plugs are inclined on the front and rear sections of the dome equally disposed on each side of the cylinder centerline in one plane and slightly offset toward the inlet valve when viewed fore and aft. This location insures intimate contact with the cooling air and permits heat transfer from the threaded bushings to the cooler portions of the cylinder head. The finned spark-plugs used in the Cyclone engine have been developed especially to meet the requirements of this powerplant.

Working in cooperation with two of the prominent manufacturers of aircraft spark-plugs, the Wright design of finned spark-plug shown on the right in Fig. 12 was produced. The sectionalized view of this plug compared to a standard radio-shielded type of the same make is given in Fig. 13. The long-reach extension of the threaded portion provides an increase of 26 per cent of cooling surface in contact with the bronze bushing of the cylinder-head to facilitate the flow of heat from the four outer electrodes. The center electrode has a hollow spindle filled with copper bonded to the material itself, thus facilitating heat extraction from the tip within the combustion chamber. In the design of this plug careful attention has been paid to establishing a heat-flow path of minimum length from the high-temperature electrodes to a cooler section of maximum area for the dissipation of the heat energy. Cooling fins on the outer shell effectively conduct a considerable amount of heat to the air stream and also provide the means for radio-shielding the plug. This finned type of plug not only permits engine operation at appreciably lower fuel consumption at both rated power and cruising output but also is effective in reducing the average cylinder-head temperatures in the above ranges by 60 deg. fahr. During 400 hr. of experimental testing and considerably more time in flight operation there has been no single case of lead-fouling reported. The results of endurance tests running at rated as well as cruising power have shown by measurement that electrode-gap burning with the finned type of spark-plug is reduced by 50 per cent. The idling properties of the finned plug are very satisfactory due to the reversal of heat flow from the head to the electrodes during idling operation of the engine. 15 hr. of idling with 5 per cent oil in the fuel have shown an unusual freedom from fouling.

The forged Y-alloy piston illustrated in Fig. 8 is provided with deep waffle-type fins on the under-side of the head which not only add immensely to the stiffness of the structure but also cool the center of the head through conduction of heat to the waffle fins and thence to the oil spray within the crankcase. To accommodate the flow of heat from the peripheral head surface of the piston to the ring belt an adequate section of material is provided behind the ring grooves. The major portion of the heat energy absorbed by the piston head escapes by way of this path and through the rings above the piston-pin to the oil film and cylinder walls.

Three compression rings form a seal against the escape of the high-temperature gases of combustion past the piston skirt to the interior of the crankcase. Two oil-control rings in a single groove provided with drain holes above the piston-pin and one single scraper ring below the pin prevent the passage of excess oil to the combustion chamber. The upper ring belt effectively shields the bearing portions of the piston skirt from excessive heat flow and permits the thrust face to operate at a sufficiently low temperature to prevent partial destruction of the oil film at this point. Observation of this piston after hours of strenuous operation shows no appreciable metal-to-metal contact between piston lands and cylinder walls, which condition is essential to prevent distortion of the grooves and subsequent ring sticking. This observation

also showed a smooth thrust surface of the skirt indicative of low-temperature operation.

The major heat flow, therefore, as mentioned previously, occurs through the sides of the lands to the piston-rings and thence to the oil film and cylinder walls. Compression rings of proper tension are most essential to the maintenance of this heat flow as well as the seal against gas leakage. Failure on the part of the upper compression rings effectively to exercise this function quickly results in carbonization of the oil in the grooves, sticking of the rings, and the disastrous results previously described. The extreme resistance to wear of the nitrided inner wall of the cylinder barrel, which retains its initial hardness throughout the range of operating temperatures incurred, permits the use of adequate ring tension with a minimum of wear.

In addition to the influence of the combustion-chamber design on fuel consumption there is also the effect of the induc-

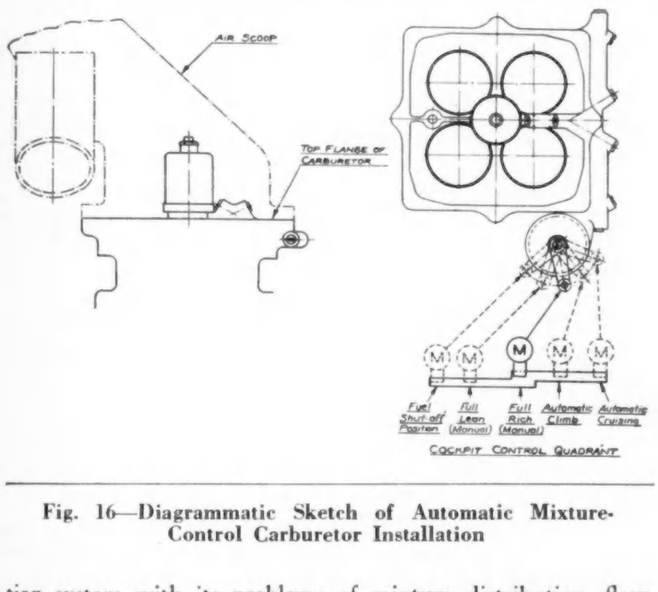


Fig. 16—Diagrammatic Sketch of Automatic Mixture-Control Carburetor Installation

tion system with its problems of mixture distribution, flow, and temperature. In the single-bank supercharged radial-type powerplant with tangential flow from a common diffuser chamber through intake pipes of equal length and form, the distribution and flow factors are inherently simplified. The matter of mixture temperature, however, intimately involves the performance and characteristics of the supercharger itself. In the conventional gear-driven type of centrifugal supercharger the speed of the impeller bears a fixed relation to the crankshaft speed of the engine. To meet the air-flow requirements of the engine for various outputs at a given engine speed it is necessary to throttle the inlet to the supercharger (usually accomplished on radial engines by the carburetor throttle) since the speed of the engine-driven impeller does not vary with constant engine revolutions per minute. Hence, for a reduced flow through the supercharger at a given tip speed of the impeller, the temperature rise of the mixture increases considerably with the resultant lowered efficiency, an inherent characteristic of centrifugal compressors. To compensate for this increased mixture temperature, when in the case of a highly supercharged engine throttled at sea level or low altitude the temperature rise has become sufficiently great to induce detonation, it is necessary to increase the fuel-air ratio for safe operation. Under such conditions the supercharger also is absorbing at low altitude the equivalent horsepower required to drive it at high altitude with no direct return to the engine in the form of increased output. Thus the specific consumption for a given grade of fuel is increased, and a sacrifice of fuel economy results from the operation of a highly supercharged engine at relatively low altitudes.

As a practical solution to this problem of high-power performance at sea level as well as at altitude with a reasonable order of fuel economy throughout the entire operating range of power output and altitude, the present model of Cyclone engine incorporates a two-speed supercharger-impeller drive mechanism changeable at the will of the pilot and embracing ratios of 7.14:1 and 10:1, impeller to crankshaft speed respectively. The lower ratio is used for take-off and sea-level operation which, in the power rating for the geared engine on 87-octane (C.F.R. method) fuel, is 930 hp. at 2200 r.p.m. and 820 hp. at 2100 r.p.m., respectively. Climbing at constant manifold pressure from sea level, the pilot arrives at a first critical altitude at 5500 ft. where the engine output at 2100 r.p.m. has increased to 850 hp. due to reduction in exhaust back pressure. At this altitude the engine is operating at full throttle in the lower blower ratio. Continuing the climb at full throttle in the low blower ratio, the power gradually declines with decreased air density until at 7200 ft. the engine output is 790 hp. at 2100 r.p.m. At this altitude the pilot may shift to the high gear ratio if he desires more power for higher altitudes. Having made the change to the 10:1 ratio by the simple shifting of a small lever in the cockpit, the pilot may continue his climb at constant manifold pressure to a second critical altitude of 12,000 ft., at which point the full-throttle output of the engine at 2100 r.p.m. is 820 hp. The two-speed impeller drive thus provides a degree of flexibility in the selection of high-power output for a wide range of altitude conditions with economic fuel consumption to a degree unattainable in a single supercharger speed and purpose installation.

Fig. 14 is a front view of the complete powerplant described in the foregoing paragraphs.

It has been pointed out previously in the discussion of the requirements for the realization of fuel economy that a second device, preferably automatic in so far as possible, is desirable

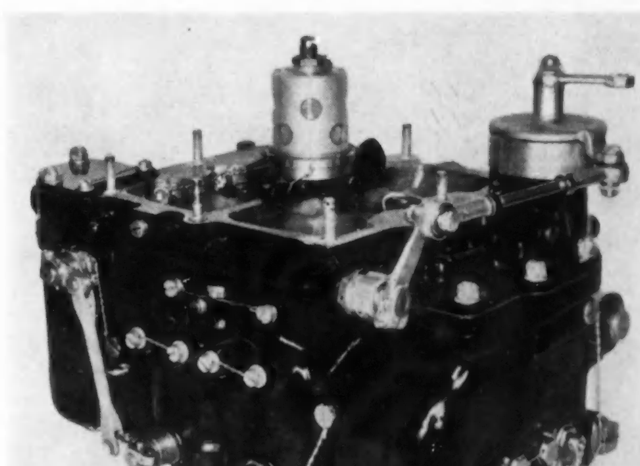


Fig. 17—Automatic Mixture Control Fitted to Bendix-Stromberg NA-F7 Carburetor

to relieve the pilot of the responsibility of continually adjusting the mixture control under varying conditions of flight to obtain an efficient fuel-air ratio. It was also noted that the increasing use of variable-pitch and constant-speed propellers and the difficulty of maintaining equivalent fuel-air ratio adjustments on multiengine installations, were outstanding factors in the demand for a means of controlling the mixture automatically at various altitudes, temperatures, and power-output requirements. Reviewing the service operations of the general types of aircraft in which automatic control of the fuel-air ratio is most desirable, it is evident that two major objectives must be met:

(1) Provision must be made for the proper fuel-air ratio to give a maximum range of power-output performance regardless of altitude, temperature, throttle opening, or other variable conditions of flight for the military-combat type of airplane. Especially in a single-seater fighter must the pilot be able to call upon the automatic mixture control to regulate the mixture strength to approximate "best setting for maximum power" with a slight margin on the rich side for the sake of acceleration and reliability under all conditions of altitude, throttle opening, or altitude of the airplane. Having set his control in the appropriate automatic-control position for best-power mixture strength the pilot must have no occasion to pay further attention to the matter of mixture regulation, but must devote himself solely to the business of fighting at rapidly changing altitudes with the assurance that he is obtaining maximum performance from his powerplant. For this type of service, considerations of fuel economy are, of course, sacrificed for optimum engine performance.

(2) In the case of aircraft for bombing service, the fuel-consumption objective becomes one of optimum economy consistent with reliable operation both per powerplant unit and complete squadron. Likewise in civil-transport operation fuel economy is a major requirement. Hence, in the provision for automatic mixture control for both types of service, there must be regulation for the proper fuel-air ratio during the period of climb at high power and low air speed to the required altitude, as well as selection of suitable mixture strength for economical cruising periods of relatively much greater duration. To meet these requirements a dual range of automatic mixture regulation obviously is necessary.

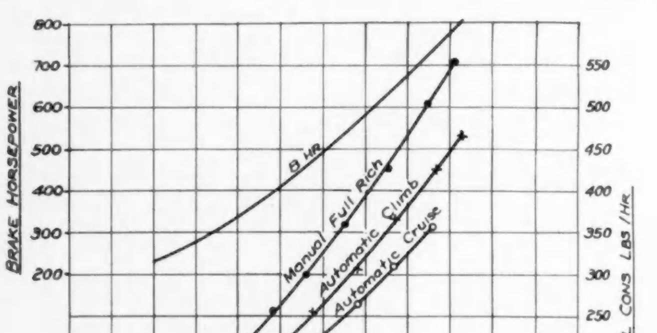


Fig. 18—Flight Propeller-Load, Fuel-Flow, and Specific Fuel Consumption Curves of Stromberg Automatic Mixture-Control Carburetor on Wright Cyclone Model R1820G5 with 92-Octane (Army method) Fuel
Compression ratio, 6.4:1; supercharger ratio, 7.14:1. Test made Jan. 7, 1936.

With the foregoing objectives in mind it will be of interest to survey briefly the practical difficulties as well as requirements that complicate the problem of automatic mixture regulation. From the standpoint of physical variations surrounding flight service it is evident that an efficient mixture-regulating device must compensate adequately for changes in the density of the air in which the aircraft and its powerplant operate, regardless of whether such changes are caused by differences in altitude, changes in temperature, or variations in the ramming effect of air into the carburetor-inlet scoop with different degrees of forward speed and angles of attack of the airplane. The control unit in all its component parts and assemblies must first of all be dependable, then light in weight, accessible, and durable. In the occasional event of improper functioning as occurs at some time or other to most mechanisms, provision must be made for uninterrupted functioning of the normal manual operation of the conventional mixture control and of the carburetor itself. The design of the unit should embrace mechanically a minimum of control rods, levers, valves, connections, joints, and so on, and a maximum of sensitivity and immediate reaction to variations in physical conditions involving pressure, temperature, and the output requirements of the powerplant.

There are in general two methods of controlling automatically the mixture strength supplied by the carburetor to the induction system of the engine:

(1) Regulating the density of the air furnished to the carburetor.

(2) Permitting the variations in density of the carburetor air supply to regulate the fuel flow.

This second principle presented certain inherent and basic advantages which led to its adoption for the development of the automatic control described herewith. Somewhat over a year and a half ago the engineers of the Wright and Bendix-Stromberg Cos. collaborated on the design of a device which, through the effect of changes in air density on the float-chamber pressure, controls the effective metering head of the main discharge nozzles and thus regulates the fuel flow within definite limits prescribed for various flight conditions. A fundamental consideration in the design of the device was to make it a component part of the carburetor and its metering system with the possibility as well of adapting it to carburetors already in service.

Hence the design was incorporated in the construction of the NA-F7 model, a four-barrel down-draft type which undoubtedly represents the most advanced and widely used carburetor of its kind in service today. As produced, the automatic mixture control adds but 2½ lb. to the weight of the carburetor unit and, by replacement of the upper half of the carburetor body and inclusion of the control device, the operator may have the older models of the NA-F7 carburetor in service converted for the automatic-mixture-control feature.

The Bendix-Stromberg NA-F7 down-draft carburetor is provided with four venturi with main discharge nozzles re-

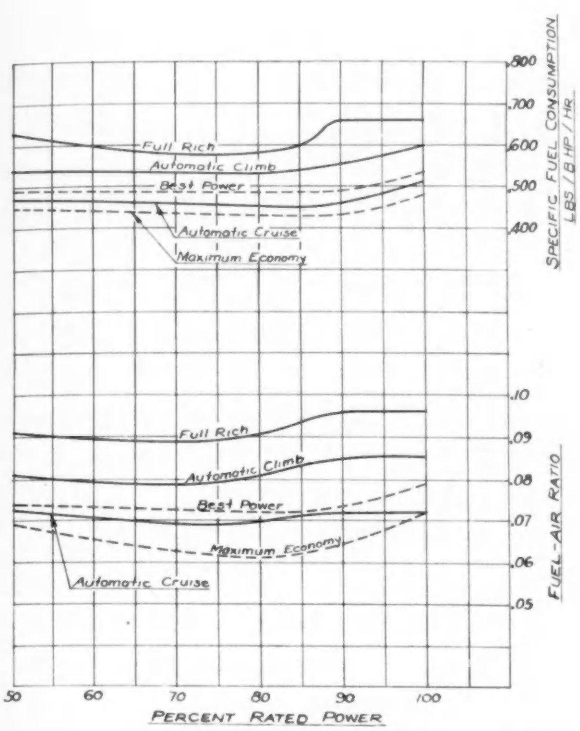


Fig. 19—Mixture Ratio and Specific Fuel Consumption versus Per Cent Rated Power of Stromberg Automatic Mixture-Control Carburetor on Wright Cyclone Model R1820G5 with 92-Octane (Army method) Fuel

Compression ratio, 6.4:1; supercharger ratio, 7.14:1 and 10.0:1. Test made Jan. 6, 1936.

ceiving fuel through four main metering jets. These main metering jets are in communication with two float chambers having a common vent system. An economizer valve located in one of the float chambers of the conventional carburetor is inter-connected with the throttles and provides an excess flow of fuel as necessary to enrich the mixture in the upper power range through two metering jets to the two adjacent venturi. Mixture control for altitude compensation or fuel economy is obtained by back suction on the float chamber as previously described.

The manner in which the functioning of the automatic mixture control has been designed into this carburetor is illustrated by the diagrammatic sketches shown in Fig. 15. A sensitive control unit consisting of a sylphon and spring-loaded plunger valve flattened on one face is contained in a duralumin housing fastened to the upper body of the carburetor and centrally located with respect to the carburetor venturi (illustrated by Fig. 16). The sylphon itself is filled partially with air and partially with a fluid whose function is to dampen vibration and to provide temperature compensation. Movement of the sylphon controls the travel of the plunger valve against spring loading and thus regulates the suction between passages *A, D, E,* and disc valve *F*. For the sake of clarity passage *E* is represented diagrammatically as exterior to the carburetor, whereas actually, it is integral with the upper half of the body.

The plunger valve itself is guided by a bushing throughout the upper portion of its length and, by a suitable contour and flattened surface at its lower extremity, it regulates through the disc valve at *F* the suction created in float chamber *H* through the action of the suction nozzle via passage *C*, to the extent necessary to give a constant fuel-air ratio as the air density at *A* varies. The space at *A* is in communication through slots surrounding the venturi with the air-horn density which varies with altitude, temperature, or a combination of these two conditions. Thus, as the air-intake density decreases with an increase in altitude or temperature, the sylphon increases in length. This expansion lowers the plunger valve and further reduces the area of the restricting passage between *D* and *E* which connects float chamber *H* with the space *A* behind the venturi. The resultant action is to increase the float-chamber depression created by the suction nozzle through *C*. Therefore the effective metering head causing fuel to flow from the main discharge nozzles is decreased and reduced mixture strength is the net result.

The restriction noted in the suction nozzle passage prevents the depression in the float chamber from ever equalling that at the main discharge nozzle so there is always an effective metering head for fuel flow under all conditions of flight. The economizer valve, previously mentioned as interconnected with the throttle to provide enrichment of the mixture at high output, has been replaced with a quick-action climb valve connected instead through a cam action to the mixture control. For all positions of the controls except when economical cruising consumption is desired, this valve is open and allows a prescribed increase in mixture strength as in the case of the conventional economizer action. When the control is set for the "automatic-cruise" position, this valve is closed and there is no flow of additional fuel through the enriching jet shown at the bottom of Fig. 15.

Referring to Fig. 16 we observe an installation sketch of the automatic-mixture-control carburetor which indicates not only the simplicity of this device but also the ease of control. It will be noted that the sylphon unit occupies very little

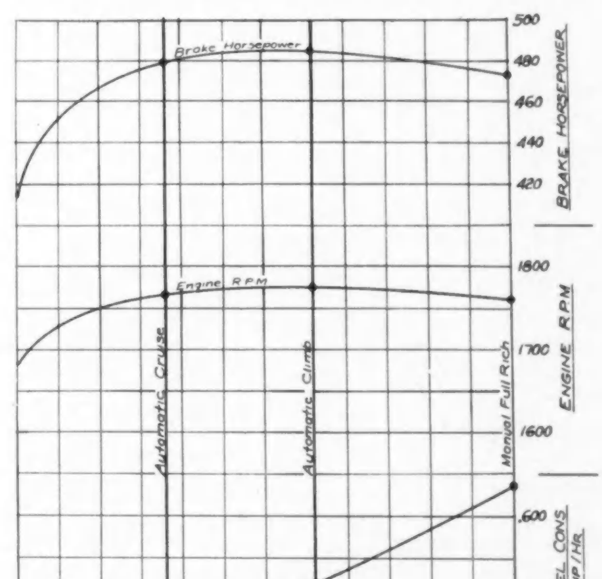


Fig. 20—Cruising-Horsepower, Engine R.P.M., and Specific Fuel Consumption Curves of Stromberg Automatic Mixture-Control Carburetor on Wright Cyclone Model R1820G5 with 92-Octane (Army method) Fuel

Compression ratio, 6.4:1; supercharger ratio, 7.14:1 and 10.0:1. Test made Jan. 6, 1936.

space and is centrally located with respect to the venturi and air scoop. A shield, omitted for the sake of clarity in the sketch and subsequent photograph, eliminates any irregularities of temperature effect due to stratification of hot and cold air within the air scoop. The accessibility of the sylphon control unit, which may be removed easily by detaching only the air scoop, is worthy of mention although failure of this part is extremely unlikely. In over a year of experience with a considerable number of these sylphon units no failure has occurred either in a carburetor installation or on vibration tests. And as has previously been stated, in the event of failure of the sylphon the carburetor continues to function as a conventional design reverting to the manual full-rich position should the automatic-mixture-control unit become inoperative.

The control arrangement for both carburetor and cockpit quadrant is shown in the right-hand view of Fig. 16. The lever actuating the disc control valve has five locations corresponding to the positions of the cockpit mixture-control lever illustrated in the lower part of Fig. 16. With the cockpit control in the "automatic cruise" position the disc control-valve lever is against the stop at the extreme end of its counter-clockwise travel. Moving the cockpit mixture-control lever to the "automatic climb" position rotates the disc control valve 15 deg. in a clockwise direction where it engages a ball latch for definite location. For a "full rich" position of the cockpit mixture-control lever, the disc control valve moves another 15 deg. in a clockwise direction and engages a ball latch. At this point the cockpit mixture-control lever

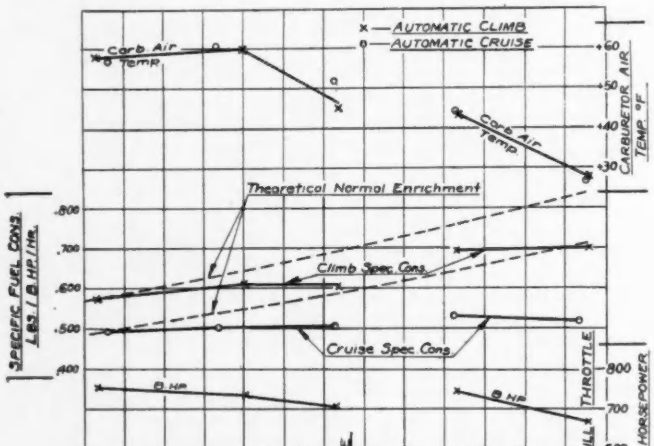


Fig. 21—Flight Test of Stromberg Automatic Mixture-Control Carburetor on Wright Cyclone Model R1820G5 with 92-Octane (Army method) Fuel

Compression ratio, 6.4:1; supercharger ratio, 7.14:1 and 10.0:1; carburetor air heater, full-cold. Test made Oct. 14, 1935.

is up against a stop. To bring into use the manual leaning adjustment of the mixture control the pilot must consciously and deliberately shift the cockpit mixture-control lever beyond the stop and over into the manual-adjustment range where the leaning effect is that previously described in connection with the conventional three-slot mixture control. Beyond the "full lean" position of the controls a shut-off valve may be manually engaged, which action entirely cuts off the flow of fuel to the jets and enables the engine to be stopped very quickly without running the float chamber dry or without operating the engine on an increasingly lean mixture during the conventional stopping procedure incurred by shutting off the supply of fuel from the line. As an adjunct to the control system described previously which locates by mechanical means the various positions of the mixture-control levers, it is of course possible, and for night flying probably desirable, to supplement these locations electrically with contact switches controlling significantly colored lights in the cockpit.

Returning to Fig. 15 let us investigate the functioning of the disc control valve for the various positions of its lever described previously. On the left hand side of Fig. 15 we note the four relative arrangements of the rotative and stationary plates of the disc valve which regulate the mixture strength to conform with the settings of the mixture control for operation in flight. Beginning with Position 1 for "automatic cruise", we note that the rotative plate is so disposed by virtue of its contour with respect to the fixed plate that the float chamber *H*, already connected to the suction nozzle via passage *C*, is subject to communication with the air space *A* behind the venturi only through passages *F* and *E*, through the sylphon-controlled plunger valve, and passage *D*. The depression in float chamber *H* is thus maintained to give a constant head on the main discharge nozzles. As previously pointed out, the climb valve is closed in the automatic-cruise position of the mixture control.

In Position 2 for "automatic climb" the rotative disc is moved clockwise 15 deg. but the same relative position of the passages exists as in "automatic cruise". However, to provide enrichment of the mixture for climbing, a cam arrangement on the mixture control opens the "climb valve" and permits additional fuel to flow to the main discharge nozzles.

In Position 3 for "manual full rich" the rotative plate is moved 15 deg. further in a clockwise direction whereupon the float chamber *H* is connected to the suction nozzle and to the space *A* behind the venturi directly via passages *B*, *F*, and *C* without communication through the sylphon control valve. Under these conditions minimum depression exists in the float chamber with resultant maximum flow from the main discharge nozzles. Thus it is evident the manual-full-rich setting is independent of the functioning of the sylphon and its plunger valve.

In Position 4 for "manual full lean" the rotative plate completely blocks off the passage *C* from communication with the space *A* behind the venturi. The suction nozzle exerts its full effect as controlled by its restriction jet and is unimpeded by leakage from *A* and *B* on the float chamber, so that the maximum depression at *H* results in a minimum fuel flow at the main discharge nozzles. For partially lean positions of the mixture-control lever the passage *C* is partially covered by the special contour of the rotative plate.

For the fifth or "fuel-shut-off" position of the mixture-control lever (not illustrated) the rotative plate is moved 10 deg. beyond the manual fuel-lean position against a stop.

Through suitable plates and passages (not shown in the sketch) the float chamber is then subjected to the suction existing below the throttles. This suction is sufficiently high in the closed position of the throttles to stop completely the flow of fuel within a few seconds. Since the float chamber is not emptied, this procedure also facilitates restarting the engine.

Like most other developments in this slightly aberrated but none the less fascinating aviation industry, the automatic mixture control described above did not spring full-fledged into being. There were numerous experiments with bypass air bleeds and variable-diameter suction nozzles. The sylphon control was tested as an independent unit exterior to the carburetor, as well as in its present location, with and without a separately operated economizer, in flight and on the ground, and so forth. As a result of all this effort over a period of one and one-half years, the advantages of this system of automatic mixture control have been established and may be summarized as follows:

(1) Through the elimination of any requirement for servo-mechanism oil-pressure lines, air-tight carburetor box, shutter valves, and multiplicity of levers, a minimum of weight has been attained.

(2) There is but one small sylphon unit required, which is easily accessible and requires no complicated connections.

(3) The sylphon unit is an integral part of the carburetor and its metering system. All the passages necessary for venting are cast within the carburetor body.

(4) In the rather remote event of sylphon failure the carburetor will continue to function in a conventional manner.

(5) Due to its central location in the air-intake stream the sylphon control unit is sensitive to, and adjusts accordingly for, changes in the air density and temperatures with minimum reactionary lag. There are no heavy moving parts with resultant inertia losses.

(6) There is no restriction on density of the air at the carburetor entrance which affects power output, nor is it necessary to maintain the temperature of the induction air within narrow limits.

(7) There are no critical altitudes within normal limits covering all commercial and military operation which adversely affect the proper functioning of this automatic mixture control.

(8) The automatic mixture control unit may be adapted to existing NA-F7 carburetors by the installation of the necessary conversion parts.

Fig. 17 shows a photograph of the automatic mixture control just described as fitted to the Bendix-Stromberg NA-F7 carburetor of the latest design. A characteristic test-stand check recently run on this carburetor will undoubtedly be of interest and is plotted in Fig. 18. The upper curve represents propeller-load horsepower for flight conditions at sea level with the Cyclone engine operating on the low gear ratio of the supercharger drive. The fuel flow in pounds over a given interval of time was weighed for a series of test runs between approximately 1400 r.p.m. and 2100 r.p.m. at which the sea-level rated power of the engine is developed. The results of values obtained for the fuel flow in pounds per hour with manual "full rich", "automatic climb" and "automatic cruise" are given, and the corresponding fuel consumptions are plotted in pounds per brake horsepower hour at the bottom of Fig. 18. This test-stand check clearly shows the selective limits which are applicable to different power-output requirements of the engine for variable flight conditions.

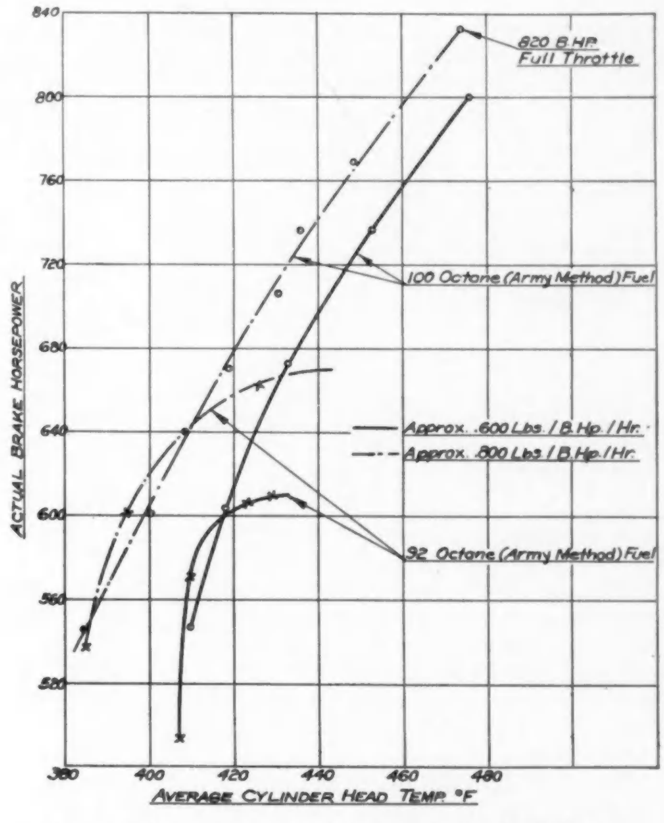


Fig. 22—Comparative Fuel Tests at Wright Field on Cyclone Engine at 1950 R.P.M. Engine Speed
Compression ratio, 6.4 :1 ; supercharger ratio, 10 :1.

Plotted against per cent of rated power, the foregoing results are shown in Fig. 19 on the basis of specific fuel consumption (top) and fuel-air ratio (bottom). The dotted curves indicate the specific fuel consumption and corresponding fuel-air ratios attainable under favorable conditions by proper manual adjustment of the mixture control for additional economy, should the pilot so desire. To illustrate the points locating the values of fuel consumption for an average power output under cruising conditions with settings in the manual-full-rich, automatic-climb, and automatic-cruise positions, a mixture-control curve based on the foregoing tests is reproduced in Fig. 20. Here we have plotted against fuel consumption in pounds per hour, the variations in brake horsepower (top), engine revolutions per minute (middle) and specific fuel consumption (bottom). The additional economy obtained by closing the climb valve in the automatic-cruise position is quite apparent in the bottom curve with no appreciable loss in power and engine speed.

In Fig. 21 there are plotted the results of a flight test with the automatic-mixture-control Stromberg carburetor on a Cyclone equipped with a two-speed supercharger and installed in the Pilgrim airplane used by the Wright Aeronautical Corp. for experimental flight testing. The object of this test was to obtain by actual measurement of a definite weight of fuel consumed over a given interval of time the effect of the automatic-climb and the automatic-cruise settings on specific fuel consumption. In the low supercharger-impeller drive ratio readings were taken at three ranges of altitude: approximately 2500 ft., 6000 ft., and 8000 ft.

Referring to the specific-fuel-consumption curves (second set from the top in Fig. 21) it will be noted that for automatic climb there is a slight enrichment with altitude which is not

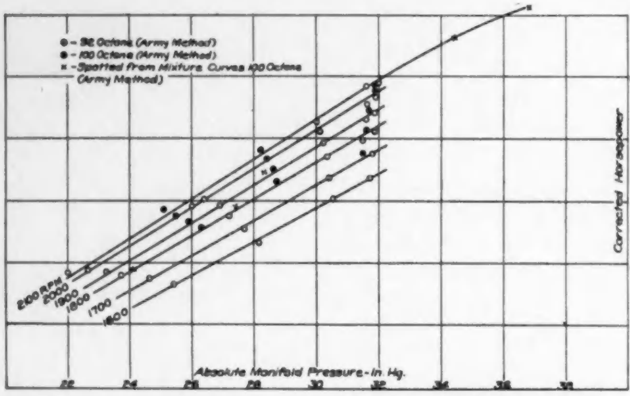


Fig. 23—Manifold-Pressure Curves of Wright Cyclone Model R1820G with 92-Octane (Army method) and 100-Octane (Army method) Fuels

Compression ratio, 7.85:1; supercharger ratio, 5.95:1. Test conducted on electric dynamometer Aug. 12, 1935.

objectionable from the standpoint of cooling at reduced air speed and improved acceleration, should the occasion arise for excess power. Under automatic-cruise setting the specific fuel consumption remains practically constant throughout the altitude range under test. It is interesting to note, as a basis of comparison, the theoretical normal enrichment calculated from the inverse variation of fuel flow with air density which would apply to the foregoing conditions of flight for the full-rich setting of the mixture control.

The points noted for the automatic-climb setting were run at the full-throttle position of the low-ratio impeller drive. Two points at slightly over 11,000 and 14,000 ft. were obtained after shifting the two-speed supercharger impeller gear to the high ratio. For the automatic-climb setting we obtain an approximately constant specific fuel consumption, possibly somewhat inclined toward the rich end but not enough to impair the maximum power output. If a leaner mixture is desired the setting may, of course, be changed to the automatic cruise, which test also shows an approximately constant value over the high altitude range.

The results of this particular flight test indicate the possibilities of the automatic mixture control for commercial operation where the present altitude limitation is approximately 14,000 ft. From the standpoint of fuel consumption it should, of course, be remembered that the automatic settings are a compromise based on a safe and economical mixture strength for operating under adverse conditions. For optimum economy under favorable conditions of flight the pilot has the option of further manual mixture-control adjustment based on the use of a mixture indicator.

In the application to military service it will, of course, be necessary to have an altitude range up to at least 30,000 ft. Although the ceiling of the experimental airplane in which the automatic mixture control has undergone testing is 19,000 ft., other flight results than those reported previously have shown that the specific fuel consumption value in both automatic climb and automatic cruise remains approximately constant; it may be expected reasonably that this condition will continue to 30,000 ft. providing difficulties with the fuel system are not encountered. It is anticipated that flight testing in a military type of airplane in the near future will demonstrate the effectiveness of this automatic mixture control for maximum engine performance at extremely high altitudes in any maneuver.

We have thus far considered the possibilities of improving fuel consumption through improved engine design, by the use of a mixture indicator to establish visual results from the adjustment of mixture strength, and by the automatic control of the fuel-air ratio to meet all conditions of flight operation. There remains but the effect of an improvement in the fuel itself for consideration.

The production of technical iso-octane early in 1934 in sufficient quantities to make possible the availability of an extremely high antiknock-rating fuel at a commercially practicable price was an outstanding accomplishment of the fuel industry. Based on the polymerization of butane (C_4H_{10}) to di-isobutylene (C_8H_{16}) with subsequent hydrogenation to give technical iso-octane (C_8H_{18}). This last product is now available at approximately $0.50 per gal. Blended with 50

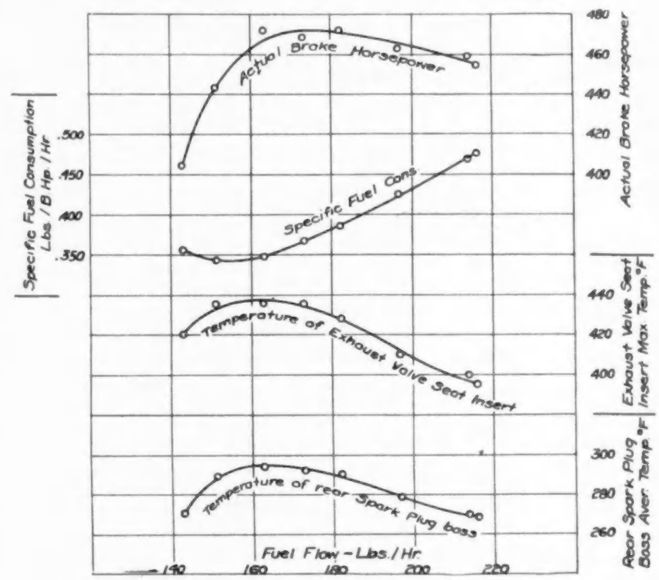


Fig. 24—Mixture-Control Curve of Wright Cyclone Model R1820G with 100-Octane (Army method) Fuel at 1800 R.P.M. and 450 Hp.

Compression ratio, 7.85:1; supercharger ratio, 5.95:1; absolute manifold pressure, 24.1 in. hg.; carburetor-air temperature, 97 deg. fahr.; cooling-air temperature, 87 deg. fahr. Showing relation between specific fuel consumption, power output, and temperatures of exhaust-valve seat insert and rear spark-plug boss. Test conducted on electric dynamometer, Aug. 12, 1935.

per cent aviation gasoline plus 3 cc. per gal. of lead tetraethyl, the resultant fuel may now be purchased with an octane rating of 100 (Army method) for approximately $0.27 per gal. in tank-wagon lots.

As a result of the foresight of the personnel of the Materiel Division, U. S. Army Air Corps, working in close cooperation with both the Shell and Standard Oil refining interests and realizing the possibilities of increased performance from aircraft engines which could utilize a fuel of considerably higher antiknock rating than the existing standard, the Air Corps prepared about two years ago a preliminary specification for 100-octane fuel. In May, 1934, procurement was made of a sufficient quantity of commercial iso-octane to permit blending with a good quality of aviation gasoline to provide sufficient fuel for some experimental tests on full-scale representative air-cooled radial aircraft engines. Lead tetraethyl to the extent of 3 cc. per gal. was added to this mixture to give a fuel with an octane rating of 100 (Army method). The complete results of the experimental tests conducted with several blends of 100-octane (Army method) fuel were reported by Lieut. F. D. Klein in a paper presented on Jan. 29, 1935, at a meeting of the Institute of the Aeronautical Sciences.

With the kind permission of the Materiel Division, U. S.

Army Air Corps, I am reproducing herewith the results of the test conducted on a Cyclone engine having a compression ratio of 6.4:1 and a supercharger gear ratio of 10:1. In conducting this test the cooling-air blast was reduced to promote detonation as indicated by the increase in cylinder-head temperatures. Variable throttle-position runs were made at 1950 r.p.m. with values of specific fuel consumption at approximately 0.60 lb. per b.hp-hr. and 0.80 lb. per b.hp-hr. In each case the throttle opening was increased and progressive readings taken until the exhaust flames indicated detonation, and the engine became rough and then "cut out". The results for this test conducted with a 100-octane (Army method) fuel composed of 50 per cent iso-octane, 50 per cent aviation gasoline plus 3 cc. per gal. of lead tetraethyl, and also for a similar test run with standard 92-octane (Army method) fuel are shown by the curves in Fig. 22.

Observing the maximum powers obtained with both grades of fuel on a specific fuel consumption of 0.80 lb. per b. hp-hr., it will be noted that the engine delivered 832 actual b. hp., with a b.m.e.p. of 185, with the 100-octane (Army method) fuel and 670 actual b. hp. with 92-octane (Army method) fuel. This increase of 24 per cent resulted in an increase from 445 to 475 deg. fahr. in cylinder-head temperature. With a specific fuel consumption of 0.60 lb. per b.hp-hr. the actual b. hp. values are 800 and 610 for the 100- and 92-octane (Army method) fuels respectively, showing an increase of 31 per cent for the higher octane fuel. In this case the difference in critical temperatures of the cylinder-heads is that between 475 deg. fahr. for the higher octane fuel and 430 deg. fahr. for the standard fuel. Thus a considerable increase in brake mean effective pressure is possible with the higher octane fuel at the same average cylinder-head temperatures.

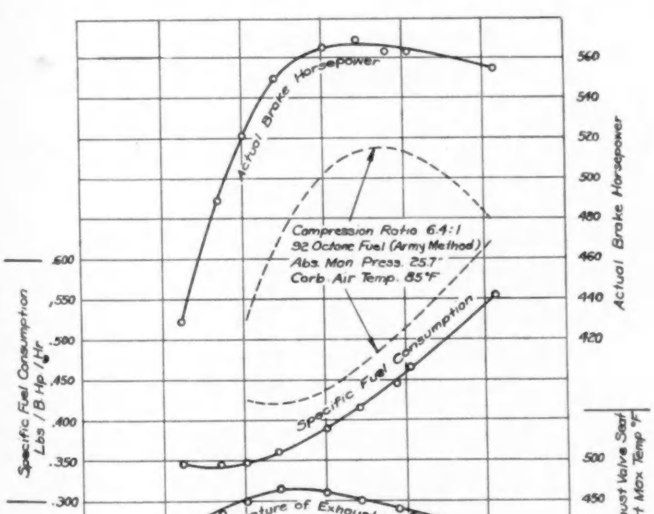


Fig. 25—Mixture-Control Curve of Wright Cyclone Model R1820G with 100-Octane (Army method) Fuel at 1800 R.P.M. and 550 Hp.

Compression ratio, 7.85:1; supercharger ratio, 5.95:1; absolute manifold pressure, 27.4 in. hg.; carburetor-air temperature, 100 deg. fahr.; cooling-air temperature, 90 deg. fahr. Showing relation between specific fuel consumption, power output, and temperatures of exhaust-valve seat insert and rear spark-plug boss. Also comparison with 92-octane (Army method) fuel. Test conducted on electric dynamometer, Aug. 12, 1935.

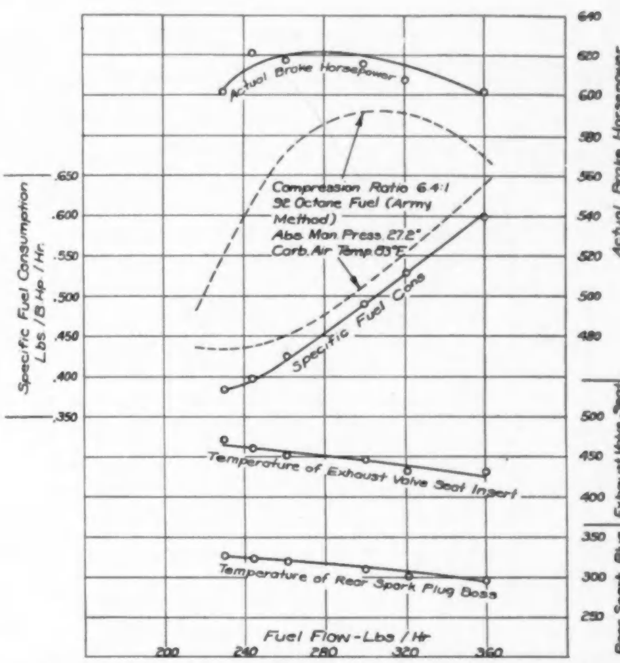


Fig. 26—Mixture-Control Curve of Wright Cyclone Model R1820G with 100-Octane (Army method) Fuel at 1900 R.P.M. and 600 Hp.

Compression ratio, 7.85:1; supercharger ratio, 5.95:1; absolute manifold pressure, 28.3 in. hg.; carburetor-air temperature, 102 deg. fahr.; cooling-air temperature, 91 deg. fahr. Showing relation between specific fuel consumption, power output, and temperatures of exhaust-valve seat insert and rear spark-plug boss. Also comparison with 92-octane (Army method) fuel. Test conducted on electric dynamometer, Aug. 12, 1935.

Referring to the specific fuel consumptions established for these tests, the values of 0.60 and 0.80 lb. per b. hp-hr. seem somewhat high and the question arises as to why the engine should deliver greater power at such a rich mixture as 0.80 lb. per b. hp-hr. This abnormal performance is undoubtedly due to the fact that the reduction in cooling-air velocity requires some compensation in the form of fuel cooling. Likewise, the use of a high supercharger gear ratio and throttling at sea level result in excessive mixture temperatures which also require some fuel enrichment for maximum output.

These tests conducted at Wright Field show the interesting possibilities of increasing the maximum output for take-off or emergency sea-level operation of powerplants having potentially a greater performance capacity which at present is restricted by the limitations of the standard existing fuels. From another, and equally practical, standpoint it would be desirable to investigate what could be expected in the way of lower specific fuel consumption in a powerplant so modified as to take advantage of the possibilities offered by the superior qualities of an ultra-high-octane fuel. Accordingly a project was set up by the Wright Aeronautical Corp. to gather experimental test data on the latest type of Cyclone engine operating on 100-octane (Army method) fuel. Through the cooperation of the Standard Oil Co. of New Jersey, sufficient fuel of this antiknock rating was obtained to carry out the preliminary test program.

During the month of August, 1935, some very interesting results were obtained on dynamometer tests conducted at the Wright plant with a Cyclone engine operating on 100-octane (Army method) fuel. The object of these tests, as indicated previously, was not only to determine some of the operating characteristics of the cylinder at high output but also to establish the possibility of satisfactory cruising operation at extremely low values of specific fuel consumption.

A standard Cyclone engine of the general type described briefly in the preceding paragraphs was accordingly assembled with special pistons of 7.85:1 compression ratio and 5.95:1 supercharger gear ratio. Thermocouples were attached to copper washers underneath the rear spark-plugs and also embedded in the lower portion of the exhaust-valve seat inserts. The following test program was established as an objective for the limited amount of fuel available:

(1) Run a series of manifold-pressure curves versus horsepower at 1600, 1700, 1800, 1900, 2000, and 2100 r.p.m.

(2) Run a series of mixture-control curves at given power outputs for representative engine speeds of 1800, 1900 and 2100 r.p.m.

(3) Change the supercharger-gear ratio from 5.95:1 to 7:1 and repeat (1) and (2).

In Fig. 23 we have the results of the manifold-pressure curves versus brake horsepower at various revolutions per minute. These curves are of no special significance save to illustrate that for the given compression ratio of 7.85:1 and supercharger-gear ratio of 5.95:1 both 100-octane (Army method) and 92-octane (Army method) fuels give practically equal power output for equivalent manifold pressures. The potential advantage of 100-octane (Army method) fuel in improving the engine performance from the standpoint of higher power output becomes increasingly apparent with higher supercharger gear ratios which permit substantial boosting of the manifold pressure. Unfortunately the supply of fuel used in these tests was exhausted before a similar set of curves could be obtained with the 7:1 supercharger gear ratio. To illustrate the straightening of the droop in the manifold-pressure-horsepower curve caused by fairly continuous detonation which the 100-octane (Army method) fuel accomplishes through its suppressive qualities, the results of more recent tests on another Cyclone engine will be introduced later in this discussion.

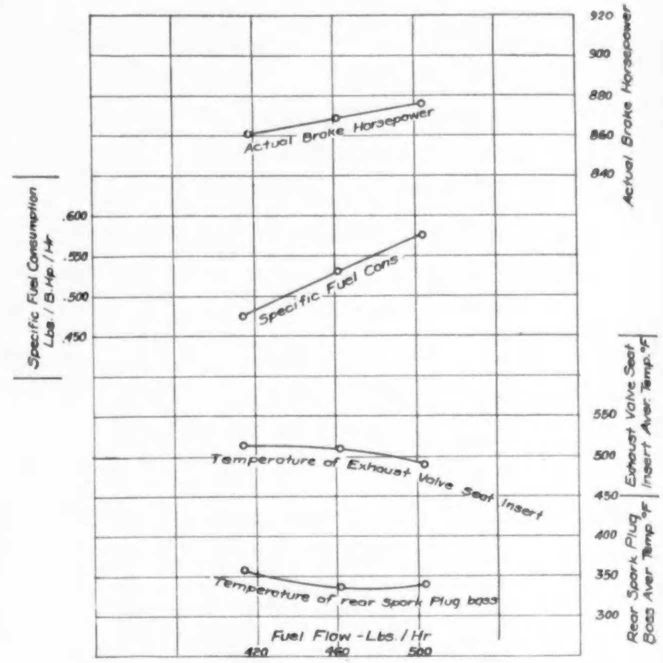


Fig. 28—Mixture-Control Curve of Wright Cyclone Model R1820G with 100-Octane (Army method) Fuel at 2100 R.P.M. and 900 Hp.

Compression ratio, 7.85:1; supercharger ratio, 5.95:1; absolute manifold pressure, 36.8 in. hg.; carburetor-air temperature, 108 deg. fahr.; cooling-air temperature, 96 deg. fahr. Showing relation between specific fuel consumption, power output, and temperatures of exhaust-valve seat insert and rear spark-plug boss. Test conducted on electric dynamometer, Aug. 12, 1935.

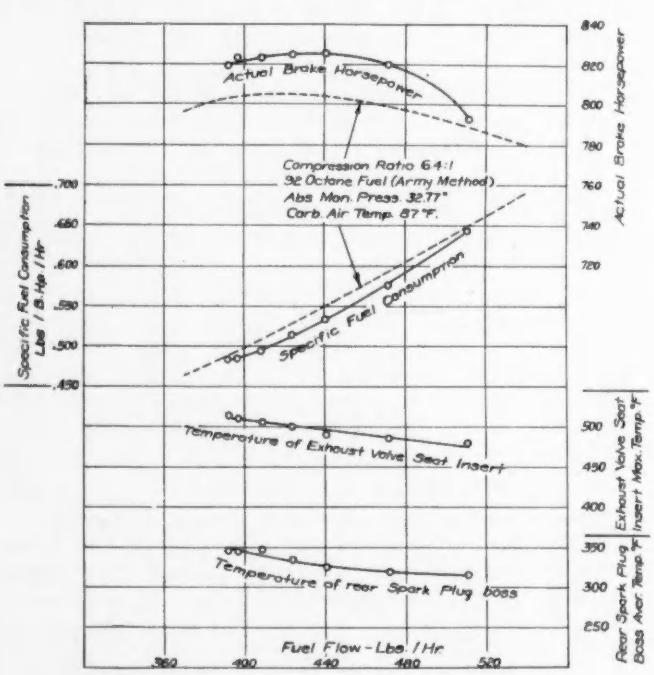


Fig. 27—Mixture-Control Curve of Wright Cyclone Model R1820G with 100-Octane (Army method) Fuel at 2100 R.P.M. and 800 Hp.

Compression ratio, 7.85:1, supercharger ratio, 5.95:1; absolute manifold pressure, 34.4 in. hg.; carburetor-air temperature, 103 deg. fahr.; cooling-air temperature, 94 deg. fahr. Showing relation between specific fuel consumption, power output, and temperatures of exhaust-valve seat insert and rear spark-plug boss. Also comparison with 92-octane (Army method) fuel. Test conducted on electric dynamometer, Aug. 12, 1935.

Returning to the possibilities of fuel economy in the cruising range of operation as the objective in item (2), let us first consider the results of the mixture-control runs illustrated in Fig. 24. Here we note the effect on actual brake horsepower, exhaust-valve seat-insert temperature, and rear spark-plug-boss temperatures of progressively decreasing the mixture strength at a throttle setting and engine speed which may be considered as a cruising output of say, 450 hp. on propeller load. For the 5.95:1 supercharger-gear ratio and 7.85:1 compression ratio, a specific fuel consumption of slightly under 0.35 lb. per b.hp-hr. was obtained with cooling-air temperature of 87 deg. fahr. and carburetor-air temperature at 97 deg. fahr. The temperatures of the exhaust-valve seat insert and the rear spark-plug boss are by no means critical even at the point of minimum fuel consumption.

Likewise in Fig. 25 we observe the specific fuel consumption obtained by manipulation of the mixture control for a cruising output of 550 hp. and 1800 r.p.m. again with the same supercharger-gear and compression ratios. Although at this stage of the test the cooling-air temperature was 90 deg. fahr. and the carburetor air temperature, 100 deg. fahr., the specific fuel consumption was again reduced to a minimum of slightly under 0.35 lb. per b. hp-hr. with the temperatures of exhaust-valve seat inserts and rear spark-plug boss remaining within permissible limits. For the sake of comparison on horsepower and specific fuel consumption values, curves have been included in dotted outline which represent actual test results of a similar nature obtained on another occasion with the use of 92-octane (Army method) fuel and 6.4:1 compression ratio pistons in the same engine.

The curves in Fig. 26 and Fig. 27 indicate the results obtained with mixture-control variations for power-output values

of 600 hp. at 1900 r.p.m. and 800 hp. at 2100 r.p.m. respectively. The same general characteristics as at lower ratings are in evidence. Due to the extremely high cooling-air temperatures of 91 and 94 deg. fahr. with resulting carburetor air temperatures of 102 and 103 deg. fahr., evidence of detonation was visible when the specific fuel consumption was reduced to 0.38 and 0.48 lb. per b. hp-hr. respectively. This same incipient condition occurred as indicated in Fig. 28 when the throttle was moved to the full-open position at 2100 r.p.m.; the actual power delivered was 860 hp., and the specific fuel consumption reduced to 0.475 lb. per b. hp-hr. In each case further reduction of the mixture strength probably could have been made and additional readings obtained. With limited experience in testing this grade of fuel, however, the test engineers concluded the test as a precautionary measure.

In accordance with item (3) of the test program the supercharger gear ratio was next changed to 7:1. Sufficient 100-octane (Army method) fuel remained from the preceding tests for only one set of mixture-control curves which were run at a cruising power output of 550 hp. at 1800 r.p.m. Again detonation was in evidence at a specific fuel consumption of 0.375 lb. per b. hp-hr. induced by high cooling-air and carburetor-air temperatures, as well as by the increased mixture temperature resulting from throttling of the supercharger and higher tip speed of the impeller. The readings obtained on this test are given in Fig. 29.

More recently, in fact on Jan. 7, 1935, a dynamometer calibration was made with 100-octane and 92-octane (Army methods) fuels on a similar type of Cyclone engine fitted with approximately 7:1 compression ratio pistons and 7.14:1 low and 10:1 high supercharger gear ratios. As illustrated in Fig. 30, the effect of the higher octane rating fuel in suppressing detonation and raising the droop in the horsepower curve at 2100 r.p.m. is increasingly apparent in the manifold-pressure range of 36 to 39 in. hg. in the lower blower ratio. The effectiveness of 100-octane (Army method) fuel in this respect, however, is most strikingly brought out by a change in supercharger gear ratio to 10:1. Here in the lower two curves at 2100 r.p.m. we note an improvement in horsepower beginning with 32 in. hg. manifold pressure. At the point where severe detonation occurred with 92-octane (Army method) fuel, namely 38 in. hg. manifold pressure, the power-output improvement due to the use of 100-octane (Army method) fuel is 9.6 per cent. Increasing the manifold pressure to 39.5 in. hg. we note an improvement of the order of 13.5 per cent with 100-octane (Army method) fuel.

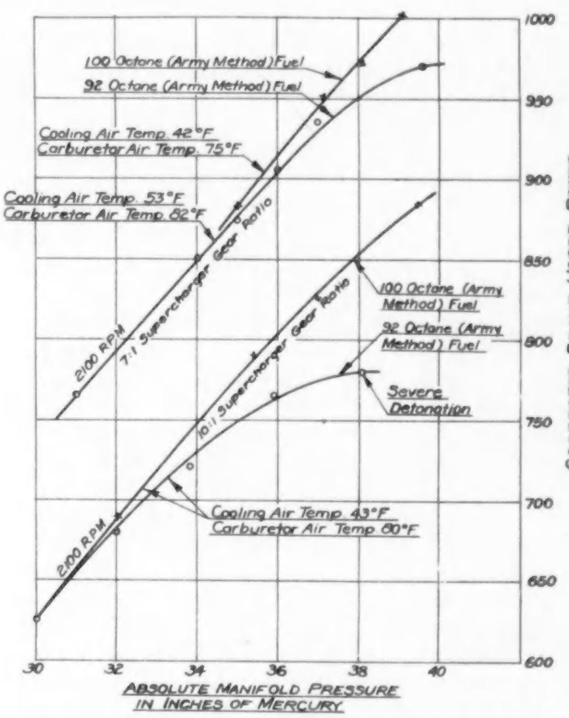


Fig. 30—Manifold-Pressure Curves of Wright Cyclone Model R1820G with 92-Octane (Army method) and 100-Octane (Army method) Fuels at 2100 R.P.M. Engine Speed

Compression ratio, 7.12:1; supercharger ratio, 7.14:1 and 10.0:1. Test conducted on electric dynamometer, Jan. 7, 1936.

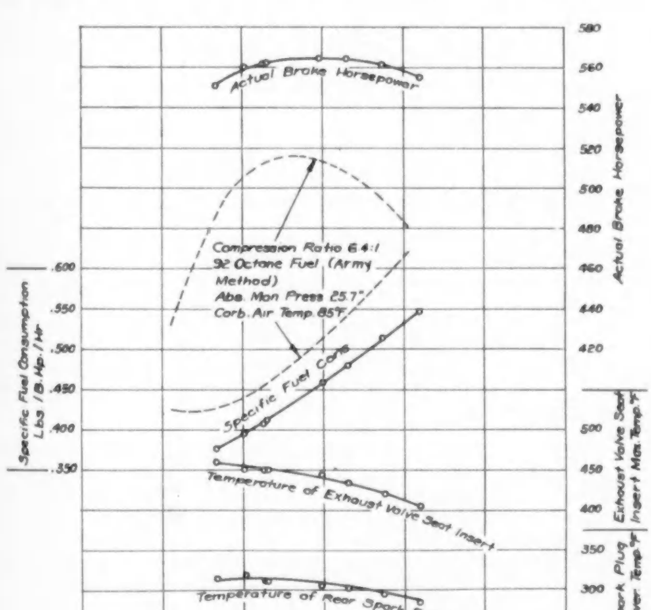


Fig. 29—Mixture-Control Curve of Wright Cyclone Model R1820G with 100-Octane (Army method) Fuel at 1800 R.P.M. and 550 Hp.

Compression ratio, 7.85:1; supercharger ratio, 7.0:1; absolute manifold pressure, 28.06 in. hg.; carburetor-air temperature, 92 deg. fahr.; cooling-air temperature, 86 deg. fahr. Showing relation between specific fuel consumption, power output, and temperatures of exhaust-valve seat insert and rear spark-plug boss. Also comparison with 92-octane (Army method) fuel. Test conducted on electric dynamometer, Aug. 12, 1935.

Thus we have indicated the possibility of increased power-output performance in the take-off manifold-pressure range on 100-octane (Army method) fuel in the 7.14:1 supercharger gear ratio for sea-level conditions and in the 10:1 supercharger gear ratio for emergency-altitude operation or take-off, for example, at Cheyenne. Fig. 31 shows the specific fuel consumptions and spark-plug-boss temperatures for the preceding calibration tests. Since the cooling-air and carburetor-air temperatures are naturally much lower than during the tests conducted last August, the values for spark-plug-boss temperatures and specific fuel consumption favor the test with the 7.14:1 supercharger gear ratio compared with the data previously obtained in the 5.95:1 ratio calibrations at equivalent output.

The results from the 100-octane (Army method) fuel reviewed in the foregoing paragraphs reflect credit both on the excellent antiknock qualities of the fuel and the superior cooling properties of the cylinder unit. They are indicative of practical fuel-consumption possibilities in the cruising range thus far acclaimed only by proponents of the Diesel-type powerplant. Admittedly the foregoing results are test-stand

data and of a somewhat preliminary nature subject to additional checking and further elaboration. And, of course, the ultimate answer involves experimental flight testing followed by service tests on the airlines and by the military forces. Nevertheless, the results obtained in the tests outlined previously certainly justify not only further activity by the engine manufacturer but also the hearty cooperation of the fuel industry and the operators.

Viewed from the actual service angle the significance of improved engine performance obtainable by the use of ultra-high-octane fuel is best interpreted by a consideration of long-distance flight operations which now have become a reality. Assuming, for example, the application of a powerplant capable of the fuel economy indicated in the foregoing tests to a four-engine seaplane, it may reasonably be expected that at a cruising output of, say 500 hp. per powerplant, a specific fuel consumption of 0.375 lb. per b.hp-hr. with the use of 100-octane (Army method) fuel will be attainable by proper adjustment of the fuel-air ratio. Compared with a specific fuel consumption of 0.475 lb. per b.hp-hr., which consumption under suitable conditions may be obtained for similar cruising requirements utilizing the 92-octane (Army method) fuel available at present, an hourly saving of 50 lb. of fuel per hr. per powerplant is possible. Based on a block-to-block cruising period of 10 hr. as possibly a representative value for trans-oceanic operation, such a total saving would be approximately 2000 lb. which, evaluated in terms of increased payload, additional cruising radius, and reduced operating costs when this fuel is generally available, should be of considerable interest to all operators.

It is sincerely to be hoped that this year will see a continued activity on the part of our fuel industry which in the past has done so splendidly in the production of high-grade fuels; a widespread awakening on the part of our operators to the possibilities of ultra-high-octane fuel so that through increased demand there may result a wider distribution together with decreased fuel costs; and finally, intensive experimentation by our engine manufacturers to produce powerplants of higher performance—all for the further advancement of the American aviation industry.

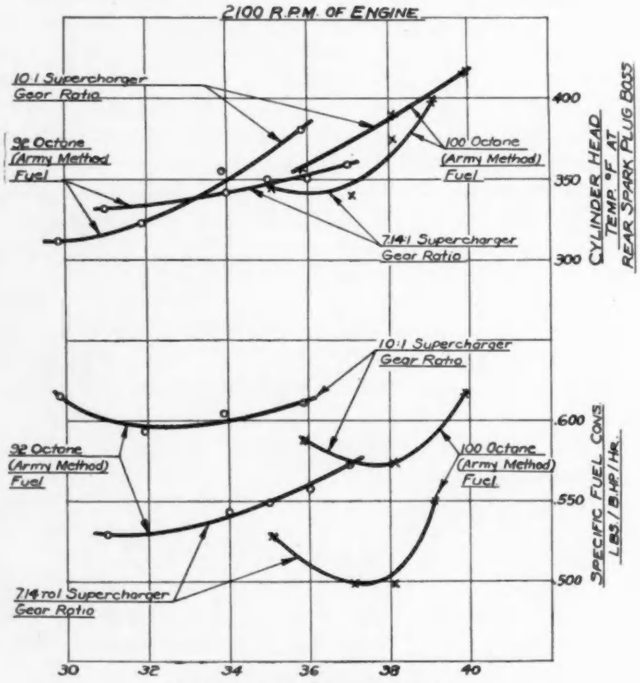


Fig. 31—Cylinder Temperatures at Rear Spark-Plug Boss and Specific Fuel Consumption versus Absolute Manifold Pressure of Wright Cyclone Model R1820G with 92-Octane (Army method) and 100-Octane (Army method) Fuels at 2100 R.P.M. Engine Speed

Compression ratio, 7.12:1; supercharger ratio, 7.14:1 and 10.0:1. Test conducted on electric dynamometer, Jan. 7, 1936.

Discussion

Leaner Mixtures Are Desirable and Possible

—**Frank C. Mock**
Bendix Products Corp.
Eclipse Aviation Corp.

IT seems quite certain that we shall shortly achieve definite reductions in fuel consumption that are entirely practical in service. In my observation, the harmful effects in lean mixtures are associated with slow or imperfect combustion, and sometimes with uneven fuel distribution to the different cylinders. We know that it is particularly bad to run an engine with a mixture so lean that the operation is "rough".

To show by example what I mean, we took a typical standard air-cooled engine of 6 : 1 compression ratio, set the throttle to give 1850 r.p.m. with the mixture ratio of maximum power for that throttle opening, and found that we could reduce the specific consumption to 0.51 lb. fuel per hp-hr. without loss of engine speed, that is, all spark-plugs operating. By leaning down the mixture to an engine speed, with this same throttle opening, of 1780 r.p.m., we were able to get to 0.46 lb. per hp-hr. consumption, at which point the engine was definitely beginning to be "rough". Using either set of spark-plugs separately, we obtained a maximum speed, with the same throttle opening, of about 1810 r.p.m. at 0.55 lb. per hp-hr., and a minimum consumption of about 0.51 lb. per hp-hr. at the falling-off point where the engine became too rough to run. This test showed that with an occasional spark-plug lapse it would have been unsafe to use a service setting below 0.52 lb. per hp-hr.

Keeping the same carburetor, manifold, and distribution (we thought this engine had fairly even distribution), we made a change in the cylinder-head design which we had found to improve combustion. Again setting the throttle at 1850 r.p.m. with both sets of spark-plugs operating and mixture setting at full power, we were able with single spark-plugs firing in each cylinder to obtain a specific consumption of 0.48 lb. per hp-hr. to 1840 r.p.m., and lean down without roughness to 1730 r.p.m. at 0.44 lb. per hp-hr. With both sets of spark-plugs operating we could obtain 1850 r.p.m. at 0.45 lb. per hp-hr. and lean down to 1750 r.p.m. at 0.41 lb. per hp-hr. and to 1600 r.p.m. at 0.43 lb. per hp-hr. before reaching the roughness limit. The effect was the same throughout the range, being more marked perhaps at the low-speed end than at high speed; for instance, it definitely responded better from quick opening of the throttle at idle. We believe that this engine would have had just as long a life at a standard cruising consumption of 0.45 or 0.46 lb. per hp-hr. as the average engine at 0.52 lb. per hp-hr., and I am convinced that the former is a standard which we will shortly attain. This engine (with special provisions to keep the pistons from burning) has undergone several months of severe service at what is believed to be a cruising consumption around 0.44 lb. per hp-hr.

With reference to mixture control, even though there is a defined limit to the leanness of mixture which can be used with present engines, it would seem desirable to maintain this limit automatically. We shall shortly have some service experience with automatic mixture regulators responsive to both intake-air pressure and temperature changes, some of which will also have automatic enrichment as the power output of the engine is increased above cruising values.

In this connection, however, we have at hand no information regarding the mixture requirements when we attempt to maintain rated power at altitude; cooling the engine is made more difficult by the reduced density of the air, but assisted by the lower external temperature and higher air speed for the same power. Experience so far seems to indicate that cooling the engine will be more difficult, which might call for a richer mixture ratio, with the same power or with the same manifold pressure, than nearer sea level. It seems to me that this subject is something we need to know more about at once, and a suitable subject for investigation which could very properly be made by one of our Government Aviation Departments.

Further development along this line will require the joint efforts of the engine designers, fuel-feed engineers, and airline operators; but I am quite optimistic about the improvement likely to be achieved in the next year or so.